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A Comparison of Candidate Seal Designs for Future Docking Systems

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A Comparison of Candidate Seal Designs for Future Docking Systems

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Abstract

NASA is developing a new docking system to support future space exploration missions to low Earth orbit, the Moon, and other destinations. A key component of this system is the seal at the main docking interface which inhibits the loss of cabin air once docking is complete. Depending on the mission, the seal must be able to dock in either a seal-on-flange or seal-on-seal configuration. Seal-on-flange mating would occur when a docking system equipped with a seal docks to a system with a flat metal flange. This would occur when a vehicle docks to a node on the International Space Station. Seal-on-seal mating would occur when two docking systems equipped with seals dock to each other. Two types of seal designs were identified for this application: Gask-O-seals and multi-piece seals. Both types of seals had a pair of seal bulbs to satisfy the redundancy requirement. A series of performance assessments and comparisons were made between the candidate seal designs indicating that they meet the requirements for leak rate and compression and adhesion loads under a range of operating conditions. Other design factors such as part count, integration into the docking system tunnel, seal-on-seal mating, and cost were also considered leading to the selection of the multi-piece seal design for the new docking system. The results of this study can be used by designers of future docking systems and other habitable volumes to select the seal design best-suited for their particular application.

Nomenclature

AO	atomic oxygen
CBM	Common Berthing Mechanism
GRC	Glenn Research Center
ISS	International Space Station
kip	one thousand lb_f
LEO	low Earth orbit
SOF	seal-on-flange
SOS	seal-on-seal

Introduction

NASA is developing a new docking system to enable in-space mating of vehicles and structures for missions to low Earth orbit (LEO) and deep space. A key component of this system is the seal at the main docking interface on the top of the docking system tunnel (Figure 1). This seal is relatively large with a diameter on the order of 50 in. (127 cm) and is compressed during the docking process. After docking, the seal must exhibit extremely low leak rates for extended missions to the International Space Station (ISS) or the Moon, for example.

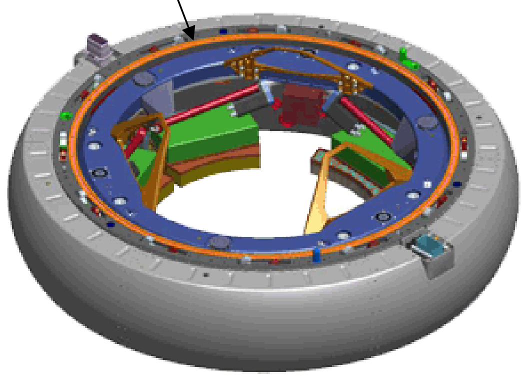

Figure 1.—Docking interface seal location.

The design for the docking interface seals has evolved with the docking system, so this trade study was conducted to ensure that the best seal design would be used for the most recent iteration of the docking system. The goals for this study were to:

- Identify candidate seal designs for the docking system,
- Assess their performance against a baseline set of requirements, and
- Summarize the key advantages and disadvantages of each candidate design for this application.

Key Requirements

The key seal requirements considered in this study are summarized in this section. Additional details on requirements for docking system seals can be found in the papers by Dunlap et al. (Refs. 1 and 2).

Leak Rate

The most important function for the docking interface seal is to minimize leakage through the interface between two mated systems. Leak rates on the order of 2.5×10^{-3} lb_m of air ($lb_{m,air}$) per day (1.1×10^{-3} kg/day) are required at this interface to ensure that the astronauts have sufficient breathable air during extended-duration missions.

Compression Loads

When two vehicles or structures mate during a mission, the seals at the interface between them will generate loads as they are compressed. To stay within the capabilities of the mechanisms that join the two vehicles together (e.g., latches), the seal loads must stay below prescribed limits so that full closure can occur without overloading the mechanisms (Figure 2). Seal compression loads per linear inch of seal must be less than approximately 70 lb_f per in. (122 N per cm) to ensure that the total compression load for a pair of 50 in.-diameter seals is less than 22 kip.

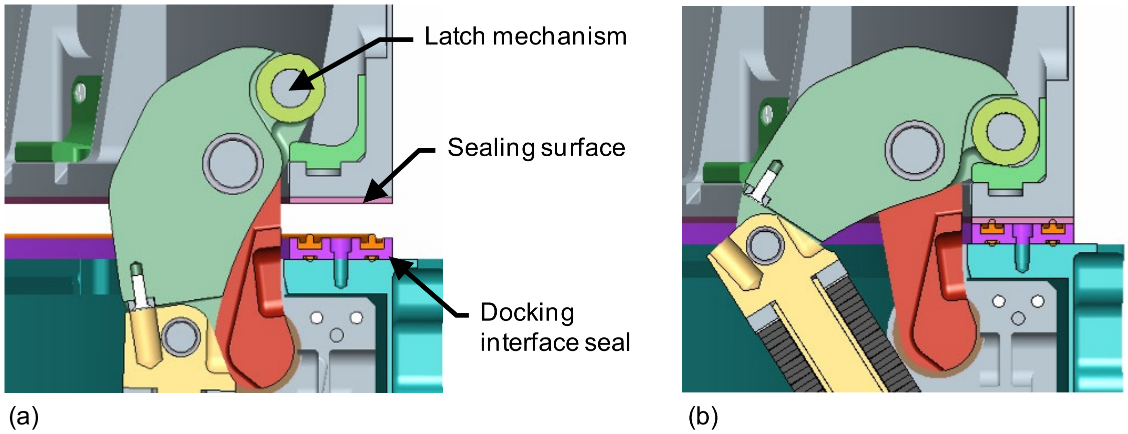

Figure 2.—Representative views of docking interface (a) just before latch mechanisms engage and (b) after latches have fully compressed the seal.

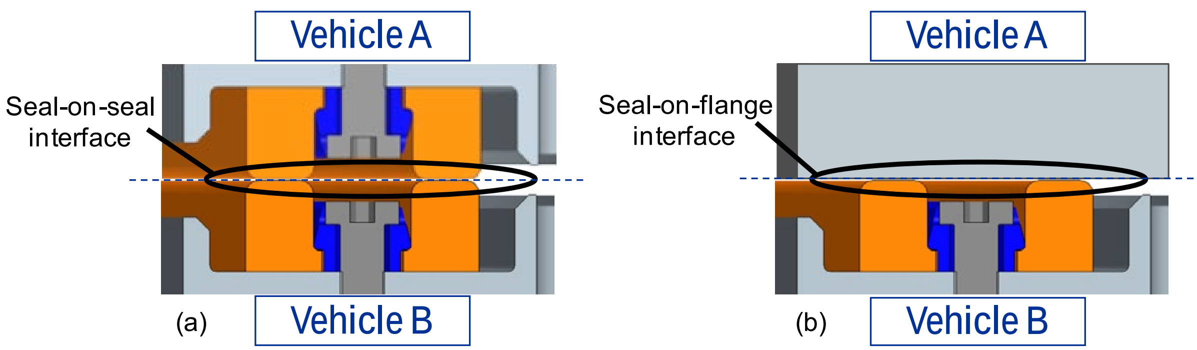

Figure 3.—Cross sections through the interface between two mated systems showing (a) seal-on-seal mating and (b) seal-on-flange mating.

Adhesion Loads

The seals must also exhibit very low adhesion forces when two mated systems separate. High seal adhesion loads could potentially restrict the ability of the systems to separate and perhaps even prevent the vehicles from undocking. High adhesion loads could also damage the seals during undocking, thereby preventing the vehicle from re-docking in the future. To prevent this from occurring, full-scale seal adhesion loads of 200 lb_f or less are desired.

Mating Configuration

Docking can occur in an androgynous seal-on-seal configuration in which both sides of the interface have seals installed or in a seal-on-flange configuration with a seal on one side of the interface and a flat, smooth metal flange on the other. Seal-on-flange mating would occur when a vehicle with a seal installed on its docking system docks to a node on the ISS with a flat metal flange. Seal-on-seal mating would occur when two vehicles equipped with seals on their docking systems dock to each other. Figure 3 illustrates both of these configurations for a candidate seal design.

Use of Redundant Sealing Features

Manned space systems require that all seal locations with diameters larger than 6.0 in. (15 cm) have a minimum of two seals for redundancy. Because future docking system seals will likely have diameters on the order of 50 in. (127 cm), redundant sealing features must be implemented. This allows the sealed interface to be single fault tolerant wherein it can still satisfy the leak rate requirement even if one of the seals has been compromised.

Engagement Conditions

Under certain conditions, the seals may not be fully compressed when they are mated resulting in metal-to-metal joint separation (or "gapping") at the sealing interface. Periodic gapping can also occur between latching mechanisms due to flange deflections around the perimeter of the docking tunnel. Either situation can occur under steady state or transient conditions, although these situations are more likely under transient conditions when dynamic loads are applied across the interface.

The sealing surfaces on each system will likely not be perfectly radially aligned during mating due to several factors:

- Manufacturing and assembly tolerances of the docking interface components, including the seals
- Differences in tunnel temperatures between mating vehicles

Radial misalignments do not typically affect seal-on-flange mating because the seal on one side of the interface is able to form an effective seal when it is compressed anywhere against the flat metal flange. However, seal-on-seal mating can be greatly affected by radial misalignments. When tolerance stackups are combined with differences in mating tunnel temperatures, radial offsets on the order of 0.125 in. (0.315 cm) between mating seal bulb centerlines can occur. Under these conditions, the amount of seal-to-seal contact is reduced resulting in less effective sealing and potentially higher leak rates.

Candidate Seal Designs

Two types of seals were evaluated in this study: a composite Gask-O-seal design produced by Parker Hannifin Corporation (San Diego, CA) and a multi-piece seal design co-invented by The University of Akron (Akron, OH) and NASA Glenn Research Center (GRC).

Gask-O-Seals

Gask-O-seals are formed by molding silicone elastomer seals directly into the grooves of a metallic (e.g., aluminum) retainer to form a single-piece seal assembly. Each seal features a bulb in the center of the groove with voids on either side to allow the bulb to spread out when it is compressed. The seal bulb is sized to prevent the incompressible rubber from completely filling the groove when it is fully compressed. This design has space flight experience and has been used as a static seal in multiple locations on the ISS including seals for the Common Berthing Mechanism (CBM) (Ref. 3), windows, hatches, and electrical connectors.

As illustrated in Figure 4, the Gask-O-seal designs evaluated in this study have dual bulbs on both the "front" and "back" sides of the retainer to meet the redundancy requirement. The seal bulbs on the front side are compressed during docking, and those on the back side are compressed when the seal assembly is installed on the docking system tunnel. In the design shown in Figure 4, the cross sections of the two front seal bulbs are identical. The back seal bulbs are also identical, although they are smaller than the front seals. However, the sizes and shapes of the seal bulbs could all be the same and can be tailored to meet the needs of a specific application.

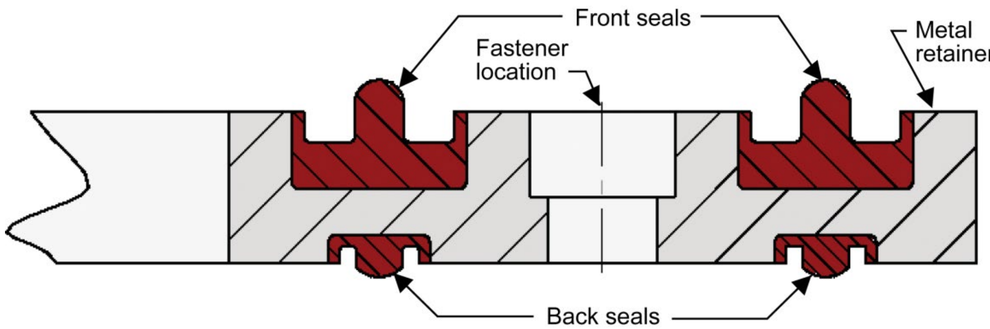

Figure 4.—Cross section through Gask-O-seal showing silicone seals molded into grooves on front and back surfaces of metal retainer.

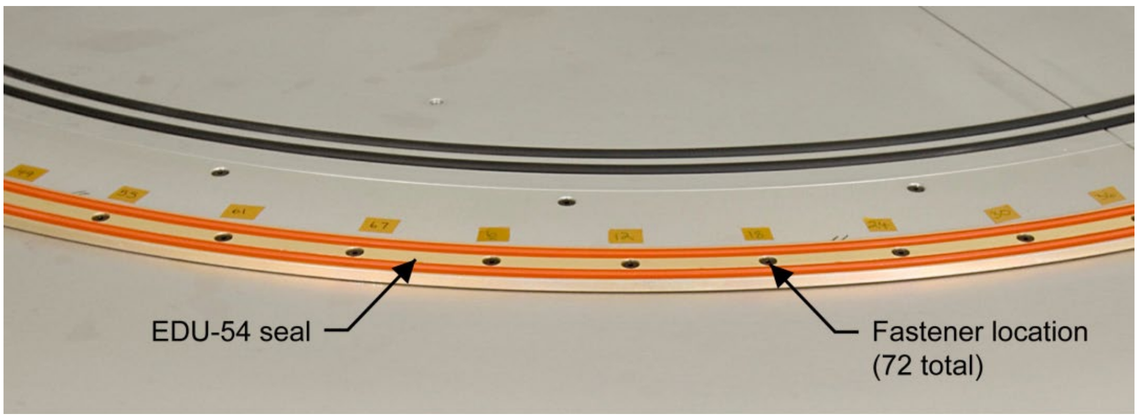

Figure 5.—Photograph of 54-in. diameter (EDU-54) Gask-O-seal installed in test apparatus showing dual front seal bulbs and fastener holes.

This seal assembly was designed to be installed directly on the top of a docking system tunnel without requiring a separate groove or flange. Alignment pin holes in the retainer (not shown) are used to align the axes of the seal and the docking system tunnel during seal installation, and fasteners are used to attach the seal assembly to the top of the tunnel. Figure 5 shows a close up view of a 54-in. diameter seal installed in a leak test apparatus at NASA GRC.

Several different Gask-O-seal designs were evaluated in this study: EDU54, EDU58-1, EDU58-2, EDU58-3, and EDU58-4. The cross sections of the seal bulbs for each design were different, but the details are proprietary and can only be described in general terms. For the EDU54 seals, the “free heights” of the seal bulbs above the surrounding metal retainer for the front and back seals were nominally 0.040 in. (1.0 mm) and 0.023 in. (0.58 mm), respectively (Ref. 4). The four EDU58 seal designs had different bulb cross sections than those for the EDU54 seals. All four EDU58 designs were similar to each other except for the heights of their front side seal bulbs. The EDU58-1 seals had the shortest seal bulbs, and those for the EDU58-2, EDU58-3, and EDU58-4 were 11, 20, and 31 percent taller than the EDU58-1 design, respectively (Ref. 5).

Multi-Piece Seal Design

The multi-piece seal design consists of an elastomer element with two seal bulbs connected by a web and a separate metal retainer with periodic bosses that pass through openings in the web (Figure 6 and Figure 7). Whereas the Gask-O-seal would be installed directly on the top of a docking system tunnel, the multi-piece seal would be installed in a groove on the top of a tunnel. A series of fasteners secures the seal assembly to the base of the seal groove.

Like the Gask-O-seal design, the elastomer seal element is molded out of silicone and has two seal bulbs to satisfy the redundancy requirement. However, unlike the Gask-O-seal, the metal retainer is a separate element (or elements for a multi-segment retainer), and the elastomer seal bulbs are not molded directly into it. The retainer in this design anchors the elastomer seal element to the tunnel and locates and centers the seal assembly in the tunnel groove.

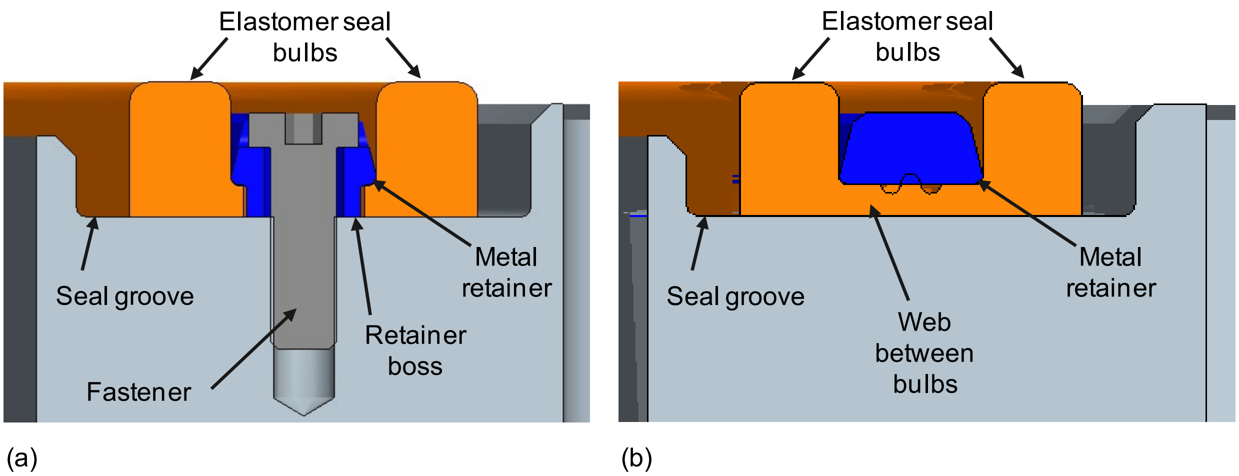

Figure 6.—Cross section through multi-piece seal assembly (a) at fastener location and (b) at location between fasteners.

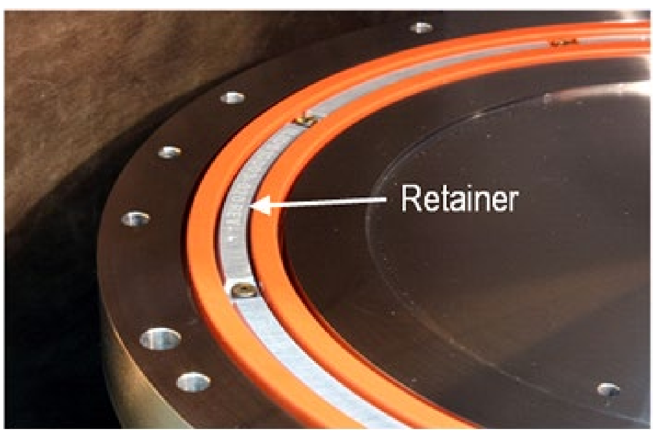

Figure 7.—Photograph of subscale multi-piece seal installed in groove in test apparatus.

Seal Materials

All performance comparisons made in this study are for seals made of S0383-70, a 70 durometer silicone material. This material has been used in a variety of space flight applications including those mentioned previously for Gask-O-seals and has been shown to meet outgassing requirements when properly cured (Ref. 6). Evaluating seals made of the same material allows comparisons to be made solely on the basis of design differences.

Although silicone seals are well-suited for space flight applications, their adhesion loads have been shown to be quite high if left untreated (Refs. 7 to 10). In many cases, these loads are beyond the push-off capabilities of planned docking system separation mechanisms. However, these same studies also showed that pre-treatment of the seals with low doses (e.g., 1×10^{20} atoms/cm^2) of atomic oxygen (AO) drastically reduced seal adhesion loads without adversely affecting seal compression loads or leak rates. Banks et al. (Refs. 11 and 12) showed that AO passivates silicone elastomers and significantly reduces the adhesion of the sealing surfaces. The current study includes comparisons of both families of seal designs (Gask-O-seals and multi-piece seals) with and without AO pretreatment.

Performance Assessments and Comparisons

The performance of the EDU54 Gask-O-seal design has been documented by Smith et al. (Ref. 4) and Wasowski et al., (Ref. 6) while Garafolo et al. (Refs. 9 and 13) and Bastrzyk et al. (Ref. 5) tested the various EDU58 designs. Multi-piece seal performance testing has been reported on by Oravec et al. (Refs. 14 and 15) and Dunlap et al. (Ref. 16). The results of these works are compared to each other and to the design requirements in the sections below.

Leak Rate

Effects of Mating Configuration

Figure 8 compares the leak rates for EDU54 (Refs. 4 and 6) and EDU58-1 (Ref. 9) Gask-O-seals and multi-piece seals (Ref. 16) across a range of temperatures from –58 to 122 °F (–50 to 50 °C) when fully compressed in a seal-on-flange configuration. The values plotted in this figure are extrapolated leak rates for 50-in. diameter versions of each seal design based on leakage measured for seals of various diameters. This was done so that fair comparisons could be made between the different designs.

For each seal design, the leak rate increased as the test temperature increased. This has been attributed to an increase in the permeability of the elastomer as the temperature rises (Ref. 13). An increase in seal leakage was also observed for the EDU58-1 seals after they were pretreated with AO. However, in all cases, the projected leak rates were well below the leakage threshold of 2.5×10^{-3} $lb_{m,air}$/day.

Leak rates in the seal-on-seal configuration have only been documented for the EDU54 Gask-O-seals. Smith et al. (Ref. 4) performed a series of tests on the EDU54 seals at room temperature and measured leak rates on the order of 1×10^{-6} $lb_{m,air}$/in./day for fully compressed seals. This corresponds to a leak rate of approximately 1.6×10^{-4} $lb_{m,air}$/day for a 50 in. diameter seal. Although this is a higher leak rate than what was projected for the same seal in a seal-on-flange configuration (3.7 to 7.7×10^{-5} $lb_{m,air}$/day), it is still an order of magnitude below the leakage threshold.

Effects of Incomplete Compression

Several studies have evaluated the ability for the candidate seal designs to meet the leak rate requirement under various levels of compression. Smith et al. (Ref. 4) showed that the EDU54 seal design formed an effective seal at room temperature when the mating sealing surfaces were gapped by as much as 0.035 in. in a seal-on-flange configuration and up to 0.075 in. when mated seal-on-seal. Garafolo et al. (Ref. 13) showed that the leak rate for the EDU58-3 seal design increased as the amount of compression

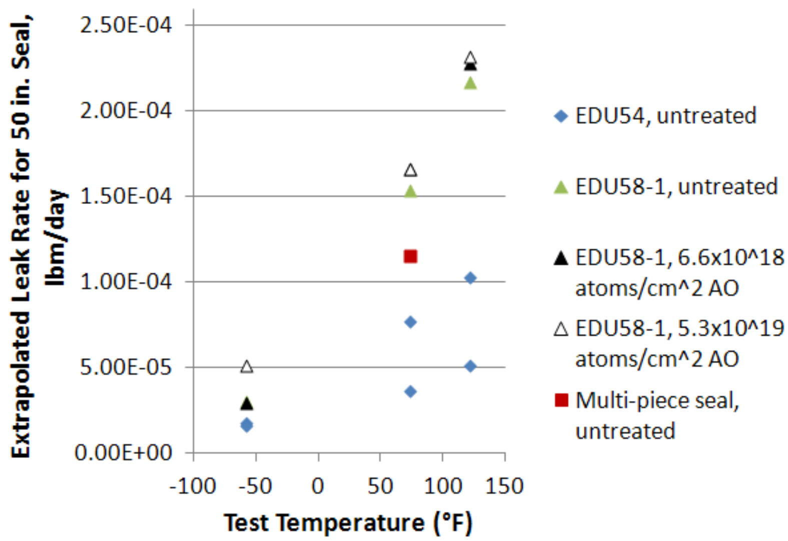

Figure 8.—Extrapolated leak rates for 50 in. diameter versions of candidate seal designs based on leakage measured for fully compressed seals in the seal-on-flange mating configuration across a range of temperatures.

on the seal was reduced for seal-on-flange mating. However, even at the warmest test temperature of 122 °F (50 °C) and only 48 percent closure, the seal still satisfied the leak rate requirement by an order of magnitude. Based on the results of these tests, both the EDU54 and EDU58-3 seal designs have been shown to be tolerant of incomplete compression and able to satisfy the leak rate requirement under those conditions.

Effects of Radial Misalignment

Radial misalignment is only an issue for the candidate seal designs when they are mated in the seal-on-seal configuration. As noted earlier, only Smith et al. (Ref. 4) has published results for any of the candidate seal designs in that configuration. In that study, the leak rate for the EDU54 seal was shown to slowly increase as the amount of radial misalignment was increased to a value of 0.120 in. However, the seal still met the leak rate requirement under those conditions. The leak rate exceeded the leakage threshold when the seal test specimens were misaligned by 0.150 in.

Compression Loads

All of the seal designs considered in this study met the compression load requirement under the conditions in which they were evaluated. Figure 9 plots compression loads measured for EDU54 (Ref. 4) and EDU58-1 (Ref. 9) Gask-O-seals and multi-piece seals (Ref. 14) in the seal-on-flange mating configuration across a range of temperatures from –58 to 167 °F (–50 to 75 °C). The values plotted in this figure represent the force required to compress the front seal bulbs for the Gask-O-seals and the entire seal bulbs for the multi-piece seals. These loads were measured from the first load cycle for the EDU54 seals and multi-piece seals and are the average of 20 load cycles for the EDU58-1 seals.

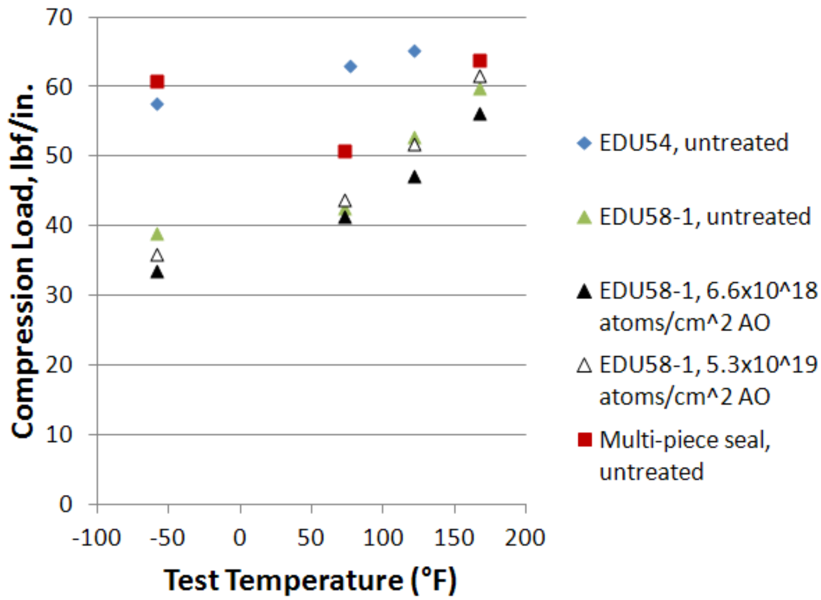

Figure 9.—Compression loads measured for candidate seal designs in the seal-on-flange mating configuration across a range of temperatures.

Several observations can be made from this figure:

- Loads measured for the multi-piece seal were comparable to those measured for the Gask-O-seals.
- For all of the Gask-O-seals that were tested, the force required to compress the seals increased with test temperature. However, this was not true for the multi-piece seal design as the load measured at 73 °F was less than those measured at –58 and 167 °F.
- EDU58-1 seals pre-treated with AO had comparable compression loads as those that were not treated.
- In all cases, the measured compression loads were below the threshold of 70 lb_f per in. of seal.

Figure 10 compares the compression loads measured for the EDU54 (Ref. 4) Gask-O-seals and multi-piece seals (Ref. 14) in the seal-on-seal mating configuration from –58 to 167 °F (–50 to 75 °C). As with Figure 9, the loads were measured from the first load cycle for these two seal designs. Several observations can be made:

- Compression loads for both designs were lower for seal-on-seal mating than for seal-on-flange mating. This was observed by both Smith (Ref. 4) and Oravec (Ref. 14) and was attributed to differences in boundary conditions at the mating interface. During seal-on-flange mating the seal interacts with a metal surface, and friction with that surface inhibits the seal from expanding in the radial direction. However, during seal-on-seal mating the two seal bulbs are able to spread laterally more easily thereby reducing compression loads.
- The multi-piece seals exhibited higher compression loads than the EDU54 seals did when tested under seal-on-seal conditions. This was in contrast with the seal-on-flange configuration in which the two seal designs exhibited similar compression loads.
- Compression loads for both designs were well below the 70 lb_f per in. requirement.

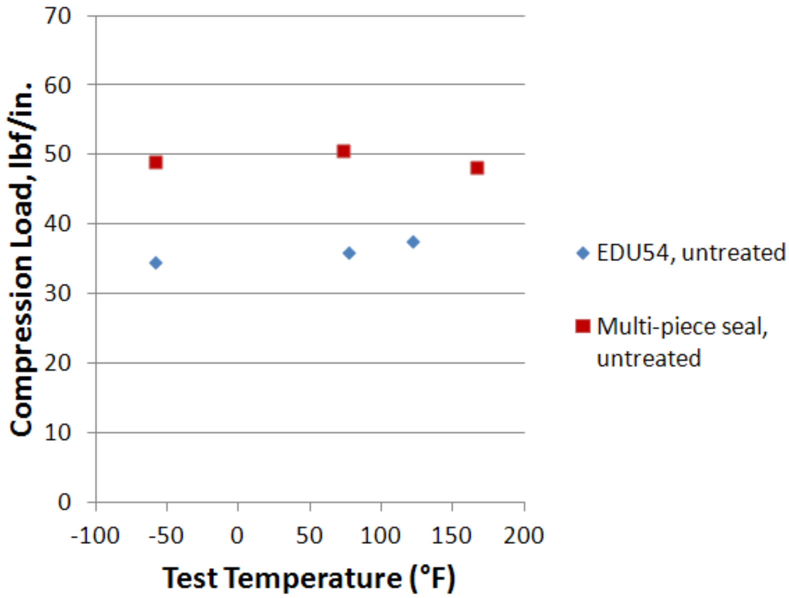

Figure 10.—Compression loads measured for candidate seal designs in the seal-on-seal mating configuration across a range of temperatures.

Adhesion Loads

Untreated Seals

As noted previously, seal adhesion loads have been shown to be quite high for untreated seals. Because of this, several studies have been conducted to assess the effects of AO pretreatment on seal adhesion loads (Refs. 9 and 15). Figure 11, Figure 12, and Figure 13 compare projected adhesion loads for EDU58 Gask-O-seals (Refs. 5 and 9) and multi-piece seals (Ref. 15) in an as-received, untreated state for dwell periods from 1 to 15 hr. The values plotted in these figures are extrapolated adhesion loads for 50-in. diameter versions of each seal design based on adhesion loads measured for subscale seals of various diameters. Note that both seal bulbs are considered in these values. These results are presented for both mating configurations, seal-on-flange (SOF) and seal-on-seal (SOS), at –58, 73, and 167 °F (–50, 23, and 75 °C).

Temperature had the greatest impact on seal adhesion loads. The projected adhesion loads for each seal design were highest at –58 °F (–50 °C). This has been attributed to an increase in the surface energy of the material as the temperature decreases (Ref. 5). Projected adhesion loads at room temperature (73 °F (23 °C)) were lower than those at –58 °F (–50 °C) for all of the seal designs (Figure 12). Although the projected adhesion loads were still fairly high at room temperature, loads for the EDU58-1, EDU58-2, and EDU58-3 seals in the seal-on-flange configuration were all below the 200 lb_f threshold. At 167 °F (75 °C), no adhesion was measured for the EDU58 seals, continuing the trend of decreasing adhesion loads with increasing temperatures. However, these results were for a dwell period of only 15 hr, and additional testing is warranted for longer dwell periods before an untreated seal would be considered for the docking seal application.

Seal bulb height also affected adhesion loads. For the EDU58 family of seal designs, the projected adhesion load increased with seal bulb height. As noted previously, the EDU58-1 seals had the shortest front seal bulbs, and the EDU58-4 seals had the tallest. As such, the EDU58-1 seals exhibited the lowest projected adhesion loads, and the EDU58-4 seals had the highest projected loads. This was expected since taller seal bulbs project a larger contact area on the mating surface when fully compressed.

The multi-piece seals exhibited comparable adhesion loads for seal-on-flange and seal-on-seal mating at the dwell times evaluated. In all cases, the projected adhesion loads exceeded the 200 lb_f threshold even for these short dwell times. During an actual mission in which the seals could remain docked for much longer periods of time (e.g., months), adhesion loads would be expected to increase. Interestingly, loads for the multi-piece seals at 167 °F were comparable to those at room temperature for the dwell periods evaluated. This is in contrast with the EDU58 seals which exhibited decreased adhesion loads at 167 °F.

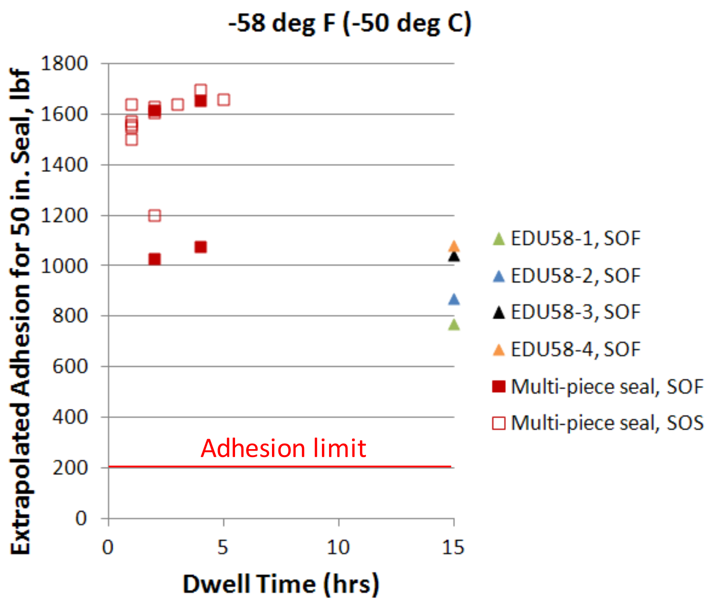

Figure 11.—Extrapolated adhesion loads for 50 in. diameter versions of candidate seal designs based on measured adhesion for untreated subscale seals in the SOF and SOS mating configurations for various dwell times at –58 °F (–50 °C).

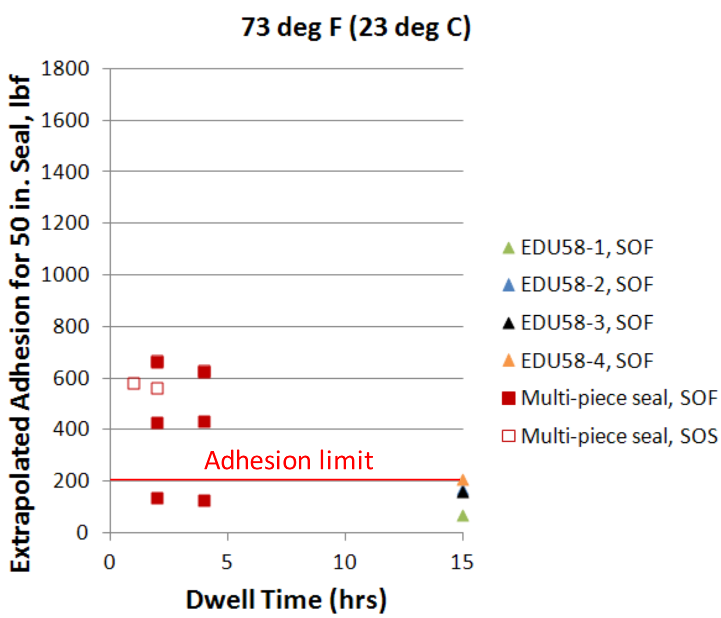

Figure 12.—Extrapolated adhesion loads for 50 in. diameter versions of candidate seal designs based on measured adhesion for untreated subscale seals in the SOF and SOS mating configurations for various dwell times at 73 °F (23 °C).

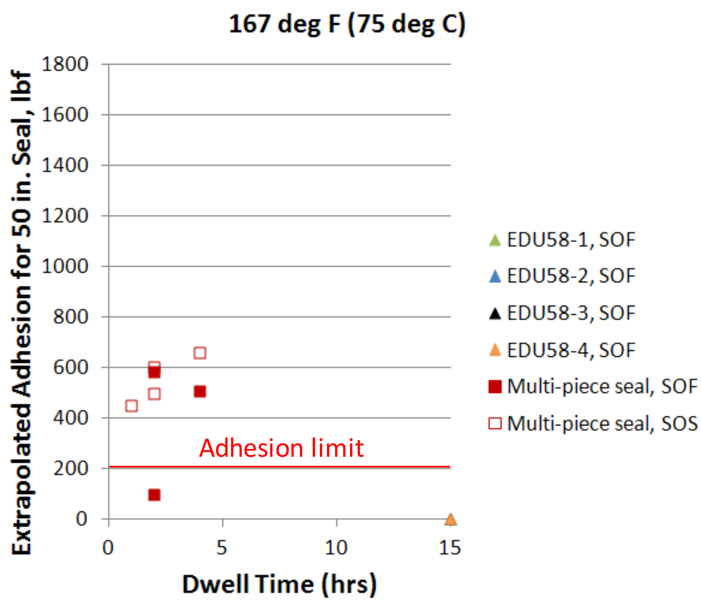

Figure 13.—Extrapolated adhesion loads for 50 in. diameter versions of candidate seal designs based on measured adhesion for untreated subscale seals in the SOF and SOS mating configurations for various dwell times at 167 °F (75 °C). (Note: All data points for EDU58 seals are 0 lb_f at 15 hr.)

In general, projected adhesion loads for the multi-piece seals were higher than those for the EDU58 seals. Factors contributing to this included the width and shape of the seal bulbs. The wider, flatter bulbs of the multi-piece seals increased their contact surface area, whereas the narrower, more rounded shape of the EDU58 seals allowed them to separate from the opposing surface more easily. Overall, projected adhesion loads for the untreated seals were higher than the adhesion load limit. Based on this, some form of adhesion reduction treatment is recommended to ensure that the seals satisfy the adhesion load requirement.

AO Pretreated Seals

Figure 14, Figure 15, and Figure 16 compare projected adhesion loads for EDU58 Gask-O-seals (Ref. 9) and multi-piece seals (Refs. 15 and 16) for various dwell periods and levels of AO pretreatment. These results are presented for both mating configurations, SOF and SOS, at –58, 73, and 167 °F (–50, 23, and 75 °C).

At all three test temperatures, the projected adhesion loads for the AO pretreated EDU58 and multi-piece seals were considerably less than those in an as-received, untreated state even after longer dwell periods. This is consistent with previous studies showing that AO pretreated seals had significantly lower adhesion loads (Refs. 9 and 15). The only test case in which the projected adhesion load exceeded the 200 lb_f limit was for a multi-piece seal pretreated to an AO fluence of 1.5×10^{20} atoms/cm^2 and compressed for 624 hr (26 days) at –58 °F (–50 °C) (Figure 14). These findings indicate a need to limit dwell times at the coldest temperatures prior to undocking or conversely the need to heat the interface after extended docking periods prior to undocking. All other cases evaluated for the EDU58 and multi-piece seals exhibited projected adhesion loads less than the 200 lb_f limit.

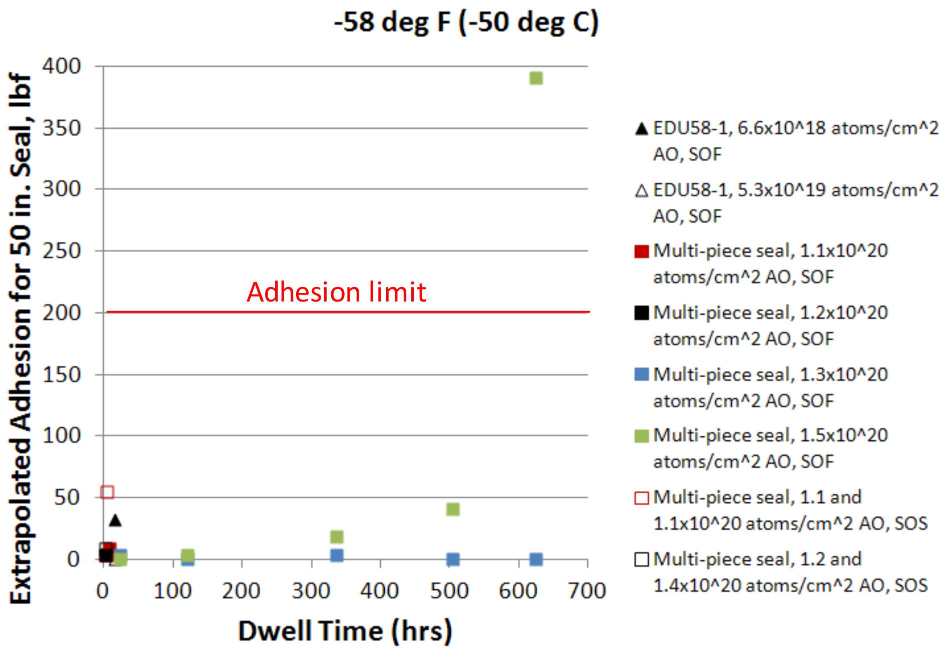

Figure 14.—Extrapolated adhesion loads for 50 in. diameter versions of candidate seal designs based on measured adhesion for AO pretreated subscale seals in the SOF and SOS mating configurations for various dwell times at –58 °F (–50 °C).

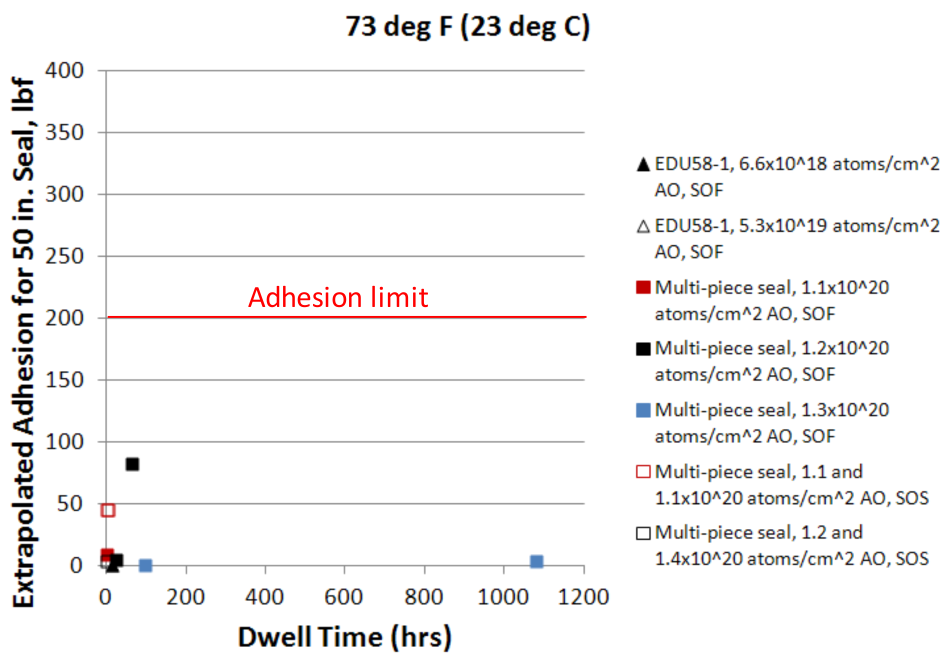

Figure 15.—Extrapolated adhesion loads for 50 in. diameter versions of candidate seal designs based on measured adhesion for AO pretreated subscale seals in the SOF and SOS mating configurations for various dwell times at 73 °F (23 °C).

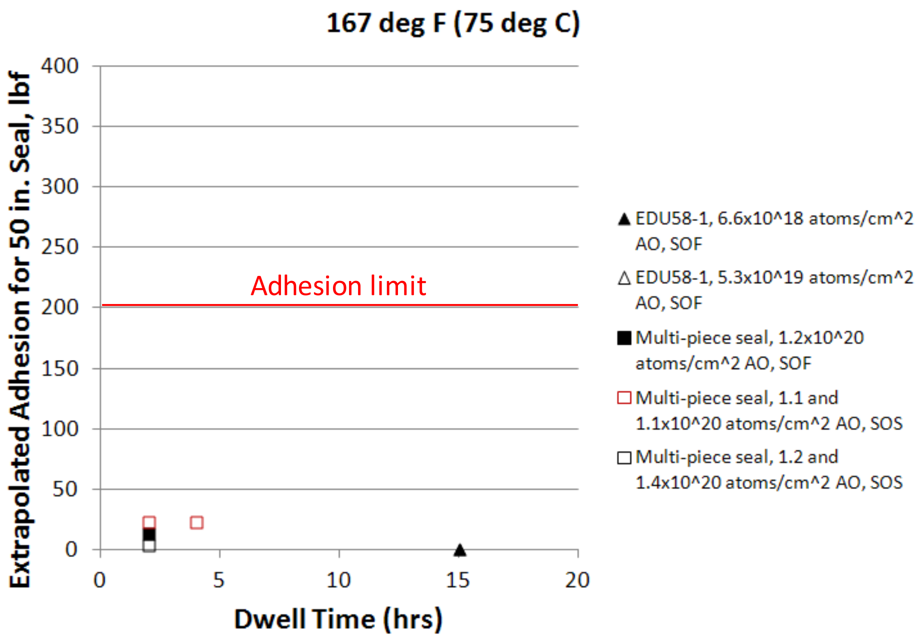

Figure 16.—Extrapolated adhesion loads for 50 in. diameter versions of candidate seal designs based on measured adhesion for AO pretreated subscale seals in the SOF and SOS mating configurations for various dwell times at 167 °F (75 °C).

Other Considerations

In addition to the performance assessments noted above, several other parameters can be used to evaluate and compare the candidate seal designs.

Part Count

Full-scale, 50-in. diameter versions of each of the candidate seal designs would likely use a comparable number of fasteners to secure them to the docking system tunnel. However, the seal designs themselves would be composed of different quantities of parts. One of the advantages of the Gask-O-seal design is that it can be fabricated in a single piece with the seal bulbs molded directly into the metal retainer. This allows the entire seal to be installed directly onto the tunnel as a single part. However, the multi-piece seal is composed of separate elements that are combined together to form the sealing system. The elastomer seal element would typically be molded as a single piece, while the separate metal retainer could be made as a single piece or in multiple segments. Thus, from a part count perspective, the candidate Gask-O-seal designs have an advantage over the multi-piece seal design.

Installation and Interaction with Docking System Tunnel

As noted earlier, Gask-O-seals would be installed directly on the top of a docking system tunnel without having to be installed in a separate groove whereas the multi-piece seal would likely need a groove in the tunnel surface. The amount of compression on the Gask-O-seal bulbs is controlled by the depth of the seal grooves in the metal retainer (Figure 4), and the load path through the interface goes directly through the seal retainer after docking (Figure 2(b)). For the multi-piece seals, though, the amount of compression on the seal bulbs is controlled by the depth of the groove in the tunnel (Figure 6). The height of the retainer is less than the depth of the groove so it does not become part of the load path after docking. This results in lower retainer stresses for the multi-piece seals since they are not subjected to the entire spectrum of docking loads.

Mating Configuration

One of the reasons that there is less seal-on-seal performance data published for the Gask-O-seal designs is that those types of designs are less amenable to seal-on-seal mating. Given the same flange width on the top of the docking system tunnel in which to fit the seal, candidate Gask-O-seal designs have narrower seal bulbs than comparable multi-piece seals due to the nature of the Gask-O-seal configuration (Figure 4). Because the seal bulbs are molded into the retainer, material must be left on either side of the bulbs to form the seal grooves. This limits the width of the seal grooves. Also, void space must be left on either side of the seal bulbs to allow them to spread out as they are compressed. These features result in narrower seal bulbs. In contrast, the bulb width for the multi-piece seal design is limited only by the width of the seal groove in the tunnel and the retainer installed between the seal bulbs (Figure 6). This configuration allows wider bulbs to be used which increases the seal's ability to accommodate larger tunnel-to-tunnel offsets and form an effective seal during seal-on-seal mating.

Cost

While the Gask-O-seal has an advantage over the multi-piece seal from a part count perspective in that the seal and retainer are integral, this feature also makes the Gask-O-seals more expensive. For seal-on-seal applications, greater control on the exact placement of the seal bulbs in their grooves is necessary in order to tolerate large tunnel-to-tunnel misalignments. Precision fixturing is required between the seal retainer and mold hardware to achieve accurate bulb positioning. This can prove challenging during seal fabrication resulting in greater part rejection and increased part costs. In contrast, the retainer for the multi-piece seals is not integrally molded thereby eliminating the need for precision fixturing during the molding process, increasing yield, and reducing fabrication costs.

The retainer for the multi-piece seal design can be fabricated as a continuous ring for precise centering in the seal groove or in a multi-piece configuration. In applications considered to-date, the wider seal bulbs for this design allowed the multi-piece retainer approach to be pursued. For a 50 in. diameter seal, six arc segments nominally 26 in. in length would be less expensive to fabricate than the single-piece retainer that would be required for a Gask-O-seal of that size.

Retainer Material Strength

Another advantage for the multi-piece seal design is that the processing steps for the elastomer and retainer elements can optimized for their unique purposes. For instance, elastomer molding requires cure cycles at elevated temperatures to achieve low outgassing properties. When performed on a Gask-O-seal, these processes can reduce the yield strength of the integral aluminum retainer thereby limiting the loads under which the seals can operate. However, decoupling the elastomer and retainer elements in the multi-piece seal design overcomes this issue as each element is processed separately.

Performance Assessments and Comparisons

Table I summarizes the performance assessments and comparisons that were made between the candidate seal designs. This includes the five specific types of Gask-O-seals (EDU54, EDU58-1, EDU58-2, EDU58-3, and EDU58-4) each of which had a different cross section. In the table, boxes that are marked in green indicate requirements that a specific seal design met or had a relative strength, while red boxes indicate that the seal design did not meet the requirement or had a relative weakness.

TABLE I.—SUMMARY OF PERFORMANCE ASSESSMENTS AND COMPARISONS FOR CANDIDATE SEAL DESIGNS.
(Note: Green boxes = Seal design met requirement or had a relative strength. Red boxes = Seal did not meet requirement or had a relative weakness.)

Evaluation factor	EDU54 Gask-O-seal		EDU58-1 Gask-O-seal		EDU58-2 Gask-O-seal		EDU58-3 Gask-O-seal		EDU58-4 Gask-O-seal		Multi-piece seal	
	Untreated	AO pretreated	Untreated	AO pretreated	Untreated	AO pretreated	Untreated	AO pretreated	Untreated	AO pretreated	Untreated	AO pretreated
Meets leak rate requirement of $2.5x10^{-3}$ lbm,air per day for 50 in. seal												
For seal-on-flange mating												
At -58°F (-50°C)	Yes		Yes	Yes			Yes					
At 73°F (23°C)	Yes		Yes	Yes			Yes				Yes	
At 122°F (50°C)	Yes		Yes	Yes			Yes					
For seal-on-seal mating												
At -58°F (-50°C)												
At 73°F (23°C)	Yes											
At 122°F (50°C)												
Under incomplete compression	SOF: Yes for up to 0.035 in. gap; SOS: Yes for up to 0.075 in. gap						SOF: Yes for 48% closure and greater					
Under radial misalignment (seal-on-seal only)	Yes for up to 0.120 in. misalignment											
Meets compression load requirement of less than 70 lbf per in. of seal												
For seal-on-flange mating												
At -58°F (-50°C)	Yes		Yes	Yes							Yes	
At 73°F (23°C)	Yes		Yes	Yes							Yes	
At 122°F (50°C)	Yes		Yes	Yes								
At 167°F (75°C)			Yes	Yes							Yes	
For seal-on-seal mating												
At -58°F (-50°C)	Yes										Yes	
At 73°F (23°C)	Yes										Yes	
At 122°F (50°C)	Yes											
At 167°F (75°C)											Yes	
Meets adhesion load requirement of less than 200 lbf for 50 in. seal												
For seal-on-flange mating												
At -58°F (-50°C)			No	Yes for up to 15 hr dwell	No		No		No		No	Yes for up to 504 hr dwell
At 73°F (23°C)			Yes for up to 15 hr dwell	Yes for up to 15 hr dwell	Yes for up to 15 hr dwell		Yes for up to 15 hr dwell		No		No	Yes for up to 1080 hr dwell
At 167°F (75°C)			Yes for up to 15 hr dwell	Yes for up to 15 hr dwell	Yes for up to 15 hr dwell		Yes for up to 15 hr dwell		Yes for up to 15 hr dwell		No	Yes for up to 2 hr dwell
For seal-on-seal mating												
At -58°F (-50°C)											No	Yes for up to 4 hr dwell
At 73°F (23°C)											No	Yes for up to 4 hr dwell
At 167°F (75°C)											No	Yes for up to 4 hr dwell
Part count	Single-piece assembly										Multi-piece assembly	
Installation & interaction with docking system tunnel	Can be installed directly on docking system tunnel without separate groove										Requires groove in docking system tunnel	
Mating configuration	Narrower bulbs are less amenable for seal-on-seal mating										Wider bulbs are more effective for seal-on-seal mating	
Cost	Single-piece retainer makes seal more expensive										Multi-piece retainer makes seal less expensive	
Retainer material strength	Integral design causes reduction in retainer strength during elastomer cure process										Retainer processed separately from elastomer element and maintains strength	

Summary and Conclusions

NASA is developing advanced, space-rated vacuum seals for future docking systems to seal the interfaces between mated vehicles and structures for missions to LEO and deep space. Two main types of seal designs were identified for this application: Gask-O-seals and multi-piece seals. Both types of seals had a pair of seal bulbs to satisfy the redundancy requirement. Based on the performance assessments and comparisons described above, the following conclusions and observations were made:

1. Several of the Gask-O-seal designs (EDU54, EDU58-1, and EDU58-3) satisfied the leak rate requirement when fully compressed in the seal-on-flange configuration at –58, 73, and 122 °F (–50, 23, and 50 °C). The multi-piece seal design also met the leak rate requirement under these conditions, but published data was only available at room temperature.
2. Both the EDU54 and EDU58-3 seal designs were shown to be tolerant of incomplete compression and able to satisfy the leak rate requirement under those conditions.
3. The EDU54 Gask-O-seals met the leak rate requirement when fully compressed at room temperature in the seal-on-seal configuration. This seal design was also able to satisfy the leak rate requirement when misaligned radially by as much as 0.120 in.
4. The EDU54 and EDU58-1 Gask-O-seals and the multi-piece seals all met the compression load requirement in the seal-on-flange configuration, and the EDU54 and multi-piece seals met the requirement in the seal-on-seal configuration.
5. Higher than desired adhesion loads were projected for as-received, untreated, full-scale versions of the candidate seal designs. Based on this, some form of adhesion reduction treatment is required to ensure that the seals satisfy the adhesion load requirement.
6. Projected adhesion loads for AO pretreated EDU58 and multi-piece seals were considerably less than those tested in an as-received, untreated state even after longer dwell periods. AO pretreated multi-piece seals satisfied the adhesion requirement after dwell periods as long as 45 days at room temperature (the longest test performed to-date).
7. From a part count perspective, the single-piece Gask-O-seals would have an advantage over the multi-piece seal design. However, the large, single-piece retainer ring required for the Gask-O-seals and other molding considerations for seal-on-seal applications would likely make them more expensive.
8. Gask-O-seals can be installed directly on the top of a docking system tunnel whereas multi-piece seals require a separate groove in the tunnel surface for installation.
9. The wider seal bulbs of the multi-piece seal design make them more effective for seal-on-seal mating than the Gask-O-seals.

Based on these observations, designers of future docking systems and other habitable volumes can select the seal design best-suited for their particular application.

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14. ABSTRACT NASA is developing a new docking system to support future space exploration missions to low Earth orbit, the Moon, and other destinations. A key component of this system is the seal at the main docking interface which inhibits the loss of cabin air once docking is complete. Depending on the mission, the seal must be able to dock in either a seal-on-flange or seal-on-seal configuration. Seal-on-flange mating would occur when a docking system equipped with a seal docks to a system with a flat metal flange. This would occur when a vehicle docks to a node on the International Space Station. Seal-on-seal mating would occur when two docking systems equipped with seals dock to each other. Two types of seal designs were identified for this application: Gask-O-seals and multi-piece seals. Both types of seals had a pair of seal bulbs to satisfy the redundancy requirement. A series of performance assessments and comparisons were made between the candidate seal designs indicating that they meet the requirements for leak rate and compression and adhesion loads under a range of operating conditions. Other design factors such as part count, integration into the docking system tunnel, seal-on-seal mating, and cost were also considered leading to the selection of the multi-piece seal design for the new docking system. The results of this study can be used by designers of future docking systems and other habitable volumes to select the seal design best-suited for their particular application.					
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