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Nicholas G. Garafolo and Christopher C. Daniels
The University of Akron, Akron, Ohio

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Nicholas G. Garafolo and Christopher C. Daniels
The University of Akron
Akron, Ohio 44325

A novel docking seal was developed for the main interface seal of NASA's Low Impact Docking System (LIDS). This interface seal was designed to maintain acceptable leak rates while being exposed to the harsh environmental conditions of outer space. In this experimental evaluation, a candidate docking seal assembly called Engineering Development Unit (EDU58) was characterized and evaluated against the Constellation Project leak rate requirement. The EDU58 candidate seal assembly was manufactured from silicone elastomer S0383-70 vacuum molded in a metal retainer ring. Four seal designs were considered with unique characteristic heights. The leak rate performance was characterized through a mass point leak rate method by monitoring gas properties within an internal control volume. The leakage performance of the seals were described herein at representative docking temperatures of -50, +23, and +50$^{\circ}C$ for all four seal designs. Leak performance was also characterized at 100, 74, and 48% of full closure. For all conditions considered, the candidate seal assemblies met the Constellation Project leak rate requirement.

Nomenclature

a	Regression coefficient
AO	Atomic oxygen
B	Bias error
CBM	Common Berthing Mechanism
$CVCM$	Collected volatile condensable materials
$EDU58$	Engineering Development Unit
h	height
$LIDS$	Low Impact Docking System
$NASA$	National Aeronautics and Space Adminstration
m	Mass
p	Pressure
P	Precision error
R	Specific gas constant
RTD	Resistance temperature device
t	Time
TML	Total mass loss
T	Temperature
U	Uncertainty
UV	Ultraviolet
V	Volume
x	bulb location

Subscript

0	zeroth order
1	first order
$bulb$	bulb
$\dot{m}$	Mass Leak Rate

I. Introduction

The National Aeronautics and Space Adminstration (NASA) developed a new docking system for spacecraft. This system, called the Low Impact Docking System (LIDS), was expected to provide the interface between pressurized manned and autonomous vehicles.[1] Novel elastomer seals were developed for the main interface seal of LIDS. The characterization of developmental seals was necessary to ensure the safety of both astronauts and spacecraft equipment.

LIDS has three large seal interfaces: the bottom-tunnel seal, the mid-tunnel seal, and the main interface docking seal. Illustrations of the seal locations are shown in Figure 1. One seal was located the bottom of the docking system and provides the seal for joining the LIDS to the vehicle. The mid-tunnel seal was integral to the LIDS and joins two components of the LIDS. The seal at the top of the LIDS was the main interface seal and provides the interface for attaching one LIDS equipped vehicle to another LIDS equipped vehicle.

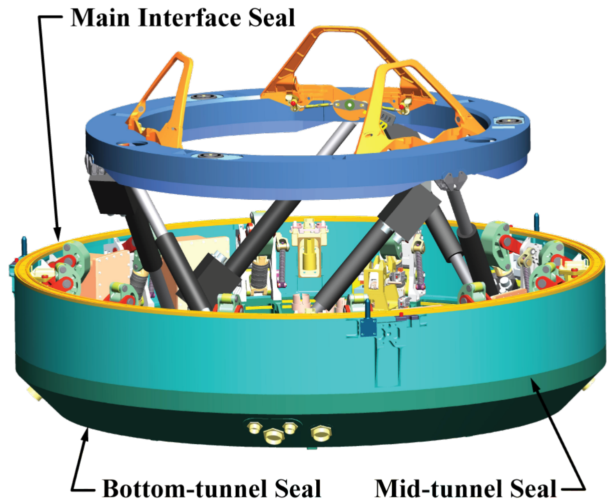


Figure 1. Illustration of the Low Impact Docking System

The main interface seal assembly, located at the top of the approximate 58 in. diameter docking system, was a quasi-static counter-face seal. This interface is designed to be joined and separated when the spacecraft docks and undocks during its mission. The seal must remain operational through repeated docking/undocking operations while also being capable of withstanding the operating load, pressure, and temperature environments.

Each of the three seals was a vacuum seal and must inhibit transport of atmospheric pressure air from within the spacecraft to its exterior (i.e., the seals must prevent the loss of air from the inside diameter of the seal while the exterior of the seal was exposed to the vacuum pressure of space). The maximum allowable leak rate of the LIDS main interface seal was 0.0025 $lb_{m,air}$ per day. This volume of air (0.0025 $lb_{m,air}$) was equivalent to approximately 80 in.^{3} at standard temperature and pressure. For a 58 in. diameter seal, the maximum allowable leak rate scales to 1.4E-5$\frac{lb_{m,air}}{day-in.}$. With the very low value of allowable leak rate, permeation of gas through the seal material was of concern and was minimized. As the LIDS and its main interface seal operate in a vacuum pressure environment, all materials must conform to NASA-STD-(I)-6016.[2] 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 pressures, as tested following the ASTM E595-076.[3]

The amount of force required to fully compress the LIDS main interface seal must be less than 140 lbf per linear inch of seal. This requirement was dictated by the latching capacity of the docking system. The mid-tunnel and bottom-tunnel seals are not held to these requirements. The LIDS main interface seal must be able to accommodated 80 docking and undocking cycles during its lifetime.

Elastomer seals provide a means to create a joint that has very low leak rates across the seal while maintaining the ability to be used repeatedly. Additionally, elastomer seals can be relatively low cost compared with other types of seals (e.g., metal seals). As the LIDS was developed to be used while in low-Earth orbit, during Trans Lunar travel, and while orbiting the Moon, the seal assemblies must be compatible with a wide range of environments. Atomic oxygen (AO) is highly reactive species and is present in low-Earth orbit. AO reacts with the surface of an elastomer seal and can embrittle the surface.

Ultraviolet (UV) radiation emitted directly from the Sun, combined with the albedo from the surface of the Earth and Moon, penetrates the bulk solid of an elastomer seal and breaks the long flexible molecular chains. The resultant short inflexible molecules tend to be brittle and can lead to cracking. The vacuum pressure can evolve the elastomer compound and continually change its properties with exposure. The environmental temperature of the LIDS was expected to be -100 to +125°C. The seal would not be required to seal across the entire exposure temperature, but it would be expected to operate across a -50 to +50°C temperature range. These requirements and exposure environments severely limit the choices of compounds suitable for docking seal applications. Therefore, the decision was made to pursue the development of silicone elastomer compound seals. These types of seals are capable of achieving very low leak rates when used as counter-face seal. They are compatible with the space environment for their expected lifetime. Select compounds are able to meet the low outgassing specifications, while most silicones can withstand the thermal environment.

The choice to use silicone, however, has the negative aspect of increased permeation through the material. Silicone is known to have a high permeation rate with respect to other typical seal material compounds. This increase in the permeation is mitigated through design.

One candidate seal is the Gask-O-Seal®, manufactured by Parker Hannifin Corporation. Gask-O-Seals® are a composite design; the elastomer compound was vacuum molded into an aluminum retainer. The seal was held into position using fasteners mounted through the metal member of the composite seal, see Figure 2.

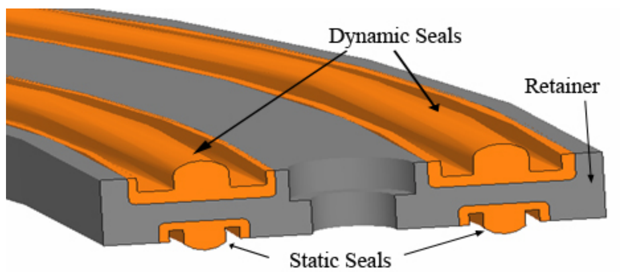


Figure 2. Illustration of EDU58 series cross section.

Experimental studies have been conducted on Gask-o-Seals® with several differing geometries and elastomer compounds, aimed at understanding the behavior of the elastomer and the leak rates corresponding to the different operating conditions that may occur during the seals lifetime. Subscale versions of the Common Berthing Mechanism (CBM) and initial Engineering Development Unit (EDU54) have been experimentally evaluated by Smith.[4] It has been shown that the leak rate of elastomer seals depends greatly on temperature. An increase increase in temperature results in an increase in leak rate. Previous docking seals, such as those used on the CBM, have met the maximum leak rate requirement. Examinations have also been conducted to characterize the leak rate and adhesion of elastomer after exposure to AO and UV radiation.[5] Leak rate dependencies on closure level have also been studied by Smith.[4] An increase in the level of closure (i.e., incomplete compression) increases the sealing performance of the candidate seal. In addition to the subscale studies noted above, near full-scale seals have been characterized and behaved similarly.[6–8]

The primary mechanism of air leakage from the main interface docking seal was permeation, where the largest contributing leakage was found through the seal rather than flow through the seal/counter-face mating interface.[4] Permeability is the measure of momentum transport in porous media.[9] Here, air travels through elastomer bulb. Permeation consists of two components, diffusion and advection. Diffusive permeation is transport driven by concentration gradients, whereas advective permeation is driven by pressure gradients. A compressible permeation approach to space seal research that encompassed both diffusion and advection was recently developed.[10–12]

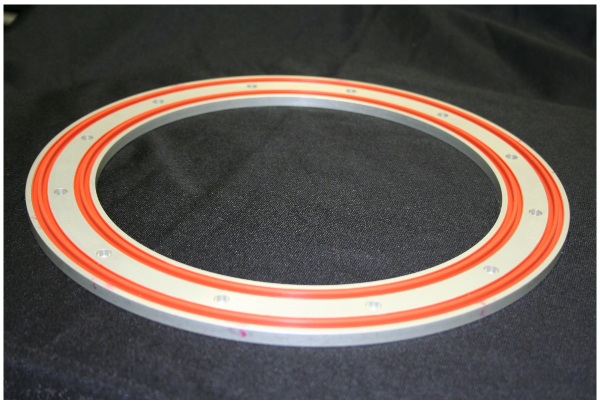
The objective of the research presented herein was to characterize the sealing performance of the Engineering Development Unit (EDU58) series of docking seals under simulated operating conditions in temperature and level of closure.

II. Experimental Setup

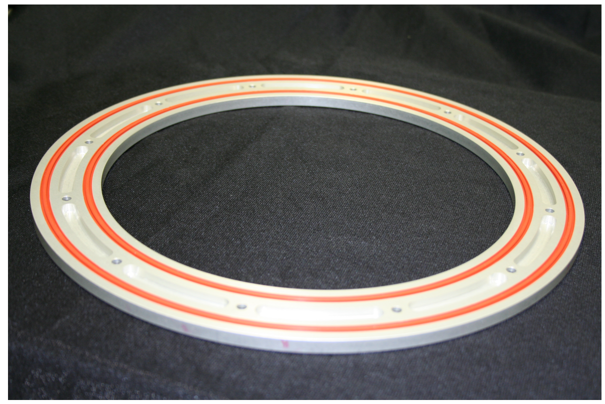
A series of experiments were conducted to characterize the leak rates of subscale candidate docking seals at specific temperatures and differing levels of compression in an elastomer on metal plate configuration. The experimental setup and procedure are detailed herein.

A. Test Specimens

The subscale candidate docking seals were Gask-O-Seals® manufactured by the Composite Sealing Systems Division of the Parker Hannifin Corporation. The seals were composite seals comprised of four elastomer bulbs vacuum molded into a metal retainer ring. An illustration of the seal showing a cross section of the molded elastomer and retainer ring is shown in Figure 2. The elastomer compound was S0383-70, manufactured by the Parker Hannifin Corporation. The metal retainer ring was manufactured from aluminium 6061-T651, which was anodized for improved corrosion resistance. The subscale test specimens were approximately 12 in. on the outside diameter. Photographs of the front side and back side of a sample test specimen are shown in Figure 3(a) and 3(b), respectively.



(a) Front side, dynamic seal



(b) Back side, static seal

Figure 3. Photograph of a subscale EDU58 test specimen.

Four bulb designs were tested. Each design had a unique and proprietary bulb height. Furthermore, the seal designs have increasing bulb heights and are noted as EDU58-1, EDU58-2, EDU58-3, and EDU58-4, respectively. The elastomer compound used for the seal bulb was verified to meet the low outgas requirements with total mass loss (TML) and collected volatile condensable materials (CVCM) values below the limits of 1.0% and 0.1%., respectively,[13] as dictated by NASA-STD-I-6016[2] and tested per ASTM E595.[3]

B. Test Apparatus

The test apparatus consisted of two plates, hermetic plumbing, and the required sensors. The test specimen was clamped between two stainless steel plates with a surface finish of 16 $\mu in.$ or better, creating an internal control volume. The seal was attached to the bottom plate with twelve 8-32 screws, compressing the back side, static seals to full closure. An illustration of the two plates clamped onto the seal is shown in Figure 4. The top plate had a vent port located between the inner and outer bulbs. This allowed for isolation and characterization of the inner seal. Dry air was supplied to the inner control volume. The pressure of this control volume was monitored by two pressure transducers with a full scale accuracy of 0.75% at a range of 0 - 35 psia. Temperature was monitored with an resistance temperature device (RTD) with an accuracy of ±0.2°C. The RTD was inserted into a small aluminum block, mounted to the stainless steel plate, and insulated from the environment in a foam block. The apparatus was enclosed in a Tenney Benchmaster-BTRC environmental chamber. The environmental chamber had a temperature range of -73 to +200°C with a control accuracy of ±0.3°C. The installation of the test specimen to the bottom plate of the test apparatus is shown in Figure 5.

In order to simulate different levels of closure of the front side, dynamic seal, shims of a known value were placed between the two fixture plates. The shims were located around the circumference of the fixture and equidistant from each other. The leak rates were characterized at 100, 74, and 48% closure, where *closure* is defined in Equation 1.

$$closure = \frac{h_{bulb} - x}{h_{bulb}} \times 100\% \tag{1}$$

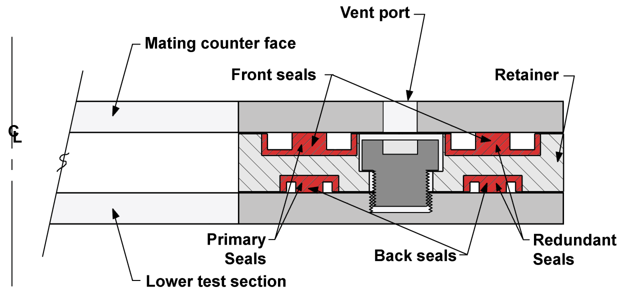


Figure 4. Illustration of two plates clamped onto a seal assembly.

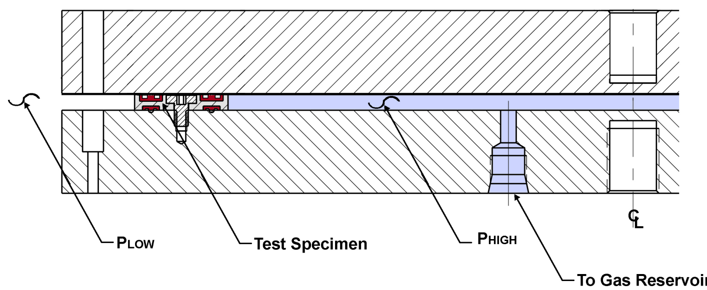


Figure 5. Illustration of test apparatus with creation of inner control volume.

where x is the distance between the metal retainer and the mating counter-face at the desired closure level and h_{bulb} is the uncompressed bulb height above the retainer. Note, full closure was metal to metal contact between the top plate and the metal retainer ring.

C. Leak Rate Calculation

The mass point leak rate method was implemented to quantify the leak rate of the subscale candidate space seals. Pressure and temperature measurements of known inner control volume of gas were monitored over time. Utilizing the ideal gas law and the definition of specific volume, the mass (m) was calculated through measurements of pressure (p), temperature (T), volume (V), compressibility factor (Z), and the specific gas constant (R).

$$m = \frac{p_{absolute} V}{(ZRT)} \tag{2}$$

The compressibility factor, Z, equal to unity was appropriate for this application, as the temperature was below $2 \times 10^3 K$.[14]

Leak rate analyses require a population of mass sample points with corresponding time stamp. An appropriate regression analysis on the population directly yields the leak rate in units of mass over time (e.g., $\frac{lb_{m,air}}{day}$). As calculated in Equation 2, the mass at each time step was determined, (t_i, m_i). A regression analysis of the mass-time population yielded the coefficients of the linear decay model:[15]

$$m\left(t\right) = a_1 t + a_0 \tag{3}$$

where m was the mass of the control volume as a function of time (t), a_1 was the leak rate, and a_0 was the initial mass of the control volume and was of no consequence. The coefficient a_1 was determined through a least-squares regression shown in Equation 4.[16]

$$a_1 = \frac{n \sum_{i=1}^{n} \left(t_i m_i\right) - \sum_{i=1}^{n} \left(t_i\right) \sum_{i=1}^{n} \left(m_i\right)}{n \sum_{i=1}^{n} \left(t_i^2\right) - \left(\sum_{i=1}^{n} \left(t_i\right)\right)^2} \tag{4}$$

The corresponding leak rate per linear inch of seal was determined by dividing the total leak rate by the mean circumference of the inner bulb. All leaks were attributed to permeation though the seal, rather than test apparatus leaks or flow across the seal interface. The complete methodology, including uncertainty analysis was detailed by Garafolo[17] and Daniels.[18]

D. Uncertainty Analysis

An uncertainty analysis is imperative for a quantifiable level of confidence in the leak rate measurement. In addition to the value of the space seal leak rate, the system uncertainty (bias error), the random uncertainty (precision error), and the confidence level must be reported.[15] Each measurement has it own bias and precision error. In this analysis, all bias and precision errors are assumed independent from each other. A comprehensive explanation of detailed uncertainty analysis can be found in Coleman[15] and with direct application to leak rate measurements in *Comprehensive Mass Point Leak Rate Technique*.[17,18]

The uncertainty analysis of the leak rate calculation included the variability in the measurement devices on the least-squares regression[15,19,20] and is shown in Equation 5. The uncertainties for each elemental measurement (i.e., pressure, temperature, time) were calculated from calibration records or manufacturer stated accuracies and propagated through to the calculation of mass, Equation 2. The comprehensive uncertainty analysis contained measures of covariance, $B_{m_i m_k}$, $B_{t_i t_k}$, and $B_{t_i m_k}$. In this study, the covariances were assumed neglectible, as each transducer was assumed completely independent of from another and that there was no covariance with the data acquisition's time control. Further discussions of these covariances are found in Coleman[15] and Brown.[21] This uncertainty, $U_{\dot{m}}$, is the uncertainty of the leak rate and is often given as a percentage, $u_{\dot{m}}$.[22]

$$\begin{aligned} U_{\dot{m}}^2 = & \sum_{i=1}^{n}\left(\frac{\partial a_1}{\partial m_i}\right)^2 P_{m_i}^2 + \sum_{i=1}^{n}\left(\frac{\partial a_1}{\partial t_i}\right)^2 P_{t_i}^2 + \sum_{i=1}^{n}\left(\frac{\partial a_1}{\partial m_i}\right)^2 B_{m_i}^2 + 2\sum_{i=1}^{n-1}\sum_{k=i+1}^{n}\left(\frac{\partial a_1}{\partial m_i}\right)\left(\frac{\partial a_1}{\partial m_k}\right) B_{m_i m_k} \\ + & \sum_{i=1}^{n}\left(\frac{\partial a_1}{\partial t_i}\right)^2 B_{t_i}^2 + 2\sum_{i=1}^{n-1}\sum_{k=i+1}^{n}\left(\frac{\partial a_1}{\partial t_i}\right)\left(\frac{\partial a_1}{\partial t_k}\right) B_{t_i t_k} + 2\sum_{i=1}^{n-1}\sum_{k=i+1}^{n}\left(\frac{\partial a_1}{\partial t_i}\right)\left(\frac{\partial a_1}{\partial m_k}\right) B_{t_i m_k} \end{aligned} \quad (5)$$

III. Experimental Results and Discussion

The leak rate per linear inch of bulb length was determined for the 12 in. EDU58 -1,-2,-3, and -4 docking seal assemblies at select temperatures and closure levels representative of operating environment. For all conditions investigated, the leak rate performance for each seal assembly met all design requirements as outline above. The maximum observed leak rate of 2.30E-6$\frac{lb_{m,air}}{day-in.}$, found at +50°C and 48% closure, was well below the requirement of 1.4E-5$\frac{lb_{m,air}}{day-in.}$. Results and discussion on the effects of temperature, design, closure, and seal design repeatability are detailed.

A. Effects of temperature on leak rate

Temperature had as significant effect on the leak rate performance of each seal; an increase in leak rate correlated to an increase in temperature. The average leak rate values per linear inch of bulb for candidate seal designs at three test temperatures are shown in Figure 6. For a given design, the 95% confidence interval for a given design's leak rate did not overlap with the 95% confidence interval of the same design at a different temperature. This suggested that there was a statistical difference between the leak rate values at the select temperatures.

The increase in leak rate was attributed to the an increase in the permeability of the elastomer and was supported by permeation modeling of elastomeric space seals.[11] The elastomer undergoes thermal expansion with an increase in test temperature, thus increasing the effective bulb width. However, the temperature effects on permeability overcome any sealing benefits in geometric changes due to thermal expansion.

B. Effects of Design

Experimental testing suggested a dependency of the leak rate on the characteristic bulb height between the EDU58 series seals. An increase in bulb height correlated with a decrease in the observe leak rate

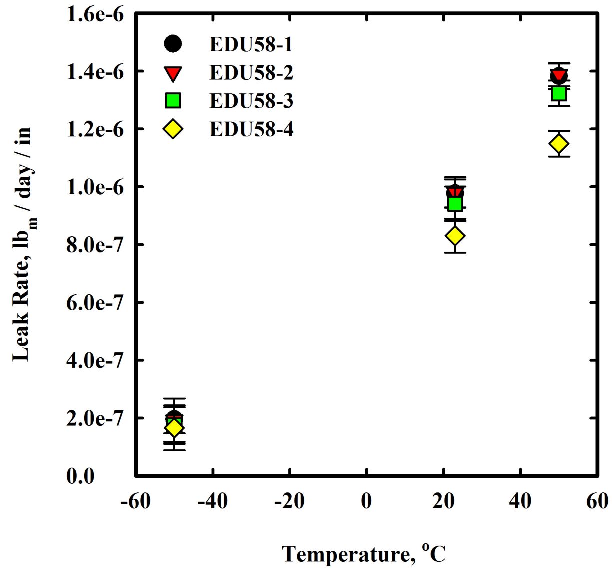


Figure 6. Comparison of average leak rates for four EDU58 seal designs at temperatures.

value, Figure 6. This was expected, as the effective seal width was wider for taller bulbs under the same displacement.

Save for the EDU58-4 seal at +50°C, there was no significant statistical difference at each temperature for the four seal assembly designs. Although it was possible to differentiate the observed leak rate values between each design, there was commonality in 95% confidence interval. It is suggested that if the fidelity of the test apparatus and data acquisition system were increased, the differences in leak rate values of the three designs would be statically significant.

It is important to note, however, that the leak rate performance is not the only metric used in the the selection of a main interface seal. The force required for full closure also needs consideration.[23]

C. Effects of closure levels on leak rate

The effects of closure level on the leak rate were determined at 100, 74, and 48% of full compression, as defined in Equation 1, for an EDU58-3 seal assembly design at each temperature. Result showed a strong dependency of compression level on leak rate, Figure 7. A decrease in closure increased the leak rate; the decrease in percent closure shortens the permeation pathway for the gas to travel and increases with wetted area available. A strong correlation between leak rate and temperature, regardless of compression level, was developed. The difference in the leak rate performance between the selected closure levels were statistically significant for +23°C and +50°C operating temperatures; the confidence intervals did not overlap. For the -50°C, differences in the leak rate were observed, however, they were not statistically significant.

D. Design Repeatability

Design manufacturing repeatability was investigated using three different seal assemblies of the same design, namely EDU58-3. The leak rates were characterized at three test temperatures (-50, +23, and +50°C) and in duplicate, for a total of six test points per temperature. Results are shown graphically in Figure 8. Given the 95% confidence interval, there was commonality in each observed leak rate of the three different EDU58-3 seals for a given temperature. This measure suggests that leak rate values of multiple seals within a specific design were not statistically different.

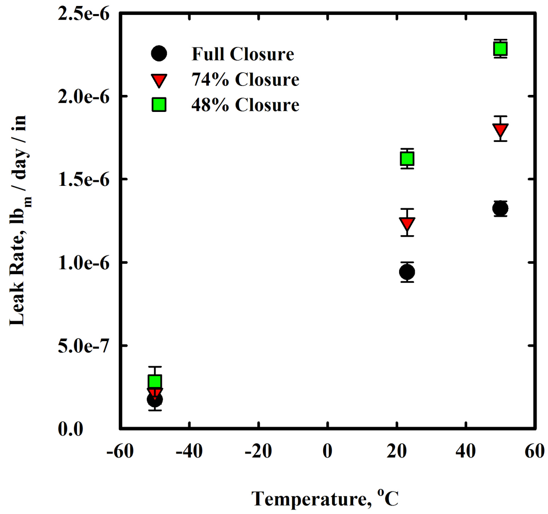


Figure 7. Average leak rates for EDU58-3 seal assembly at temperatures and various compression levels.

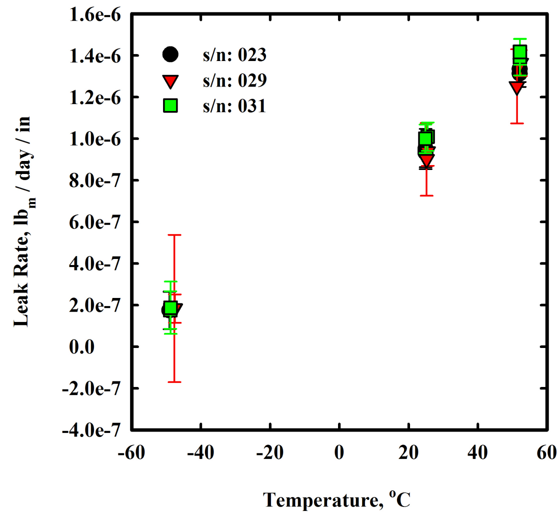


Figure 8. Leak rates of three EDU58-3 seal assemblies at temperatures.

IV. Conclusion

The performance characterization of pressure seals in spacecraft is imperative for manned spaceflight. Seals must meet or exceed acceptable air losses in a harsh vacuum environment over extreme operating conditions. A performance characterization of a candidate seal assembly for the main interface seal of the Low Impact Docking System was performed with four seals of the EDU58 design series in various compression and temperature conditions.

The following conclusions were supported with this experimental investigation:

- There exists a dependence of leak rate on temperature. An increase in test temperature was shown to increase the leak rate. The temperature effects on permeability overcome any sealing benefits in geometric changes due to thermal expansion.
- There exists a dependance of leak rate on compression. Results showed that a decrease in the level of compression increases the leak rate.
- A dependency of the leak rate on seal design was suggested. However, the leak rates of the designs were not statically different at a given temperature. It was suggested that an increase in the fidelity of the test apparatus and data acquisition system may differentiate the seal designs.
- The EDU58 series seal design met program performance requirements for all seal designs and temperatures investigated.

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14. ABSTRACT
A novel docking seal was developed for the main interface seal of NASA’s Low Impact Docking System (LIDS). This interface seal was designed to maintain acceptable leak rates while being exposed to the harsh environmental conditions of outer space. In this experimental evaluation, a candidate docking seal assembly called Engineering Development Unit (EDU58) was characterized and evaluated against the Constellation Project leak rate requirement. The EDU58 candidate seal assembly was manufactured from silicone elastomer S0383-70 vacuum molded in a metal retainer ring. Four seal designs were considered with unique characteristic heights. The leak rate performance was characterized through a mass point leak rate method by monitoring gas properties within an internal control volume. The leakage performance of the seals were described herein at representative docking temperatures of -50, +23, and +50 °C for all four seal designs. Leak performance was also characterized at 100, 74, and 48 percent of full closure. For all conditions considered, the candidate seal assemblies met the Constellation Project leak rate requirement.

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