SPACE ENVIRONMENT'S EFFECTS ON SEAL MATERIALS

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A Low Impact Docking System (LIDS) is being developed by the NASA Johnson Space Center to support future missions of the Crew Exploration Vehicle (CEV). The LIDS is androgynous, such that each system half is identical, thus any two vehicles or modules with LIDS can be coupled. Since each system half is a replica, the main interface seals must seal against each other instead of a conventional flat metal surface. These sealing surfaces are also expected to be exposed to the space environment when vehicles are not docked. The NASA Glenn Research Center (NASA GRC) is supporting this project by developing the main interface seals for the LIDS and determining the durability of candidate seal materials in the space environment. In space, the seals will be exposed to temperatures of between 50 to –50 °C, vacuum, atomic oxygen, particle and ultraviolet radiation, and micrometeoroid and orbital debris (MMOD). NASA GRC is presently engaged in determining the effects of these environments on our candidate elastomers. Since silicone rubber is the only class of seal elastomer that functions across the expected temperature range, NASA GRC is focusing on three silicone elastomers: two provided by Parker Hannifin (S0-899-50 and S0-383-70) and one from Esterline Kirkhill (ELA-SA-401). Our results from compression set, elastomer to elastomer adhesion, and seal leakage tests before and after various simulated space exposures will be presented.

Outline

- **Introduction**
  - Low Impact Docking System (LIDS).
  - LIDS main interface seal, challenges and candidate elastomers.
  - The expected mission space environment.
- **Simulating the space environments (Atomic Oxygen, Ultraviolet & Ionizing Radiation, MicroMeteoroid Orbital Debris)**
- **MicroMeteoroid Orbital Debris (MMOD) results**
- **Leak rate testing and results**
- **Adhesion testing and results**
- **Compression set testing and results**
- **Conclusions**
- **Future Work**

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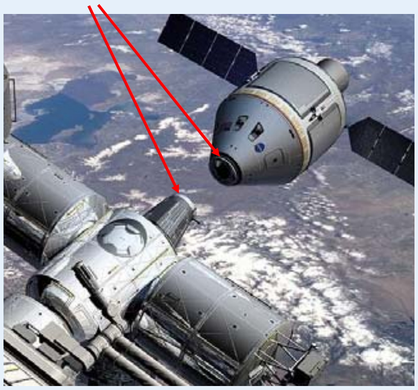
Introduction

Low Impact Docking System (LIDS)

LIDS main interface seal



- Very low leakage requirements:
  - CEV < 0.02 lbm/day
  - Apollo ~ 4.5 lbm/day
- Seals must survive long-term exposure to space.
- -50 °C to 50 °C operating range.
- Candidate silicone seal materials: Parker Hannifin S0899-50 and S0383-70, and Esterline Kirkhill XELS-SA-401.

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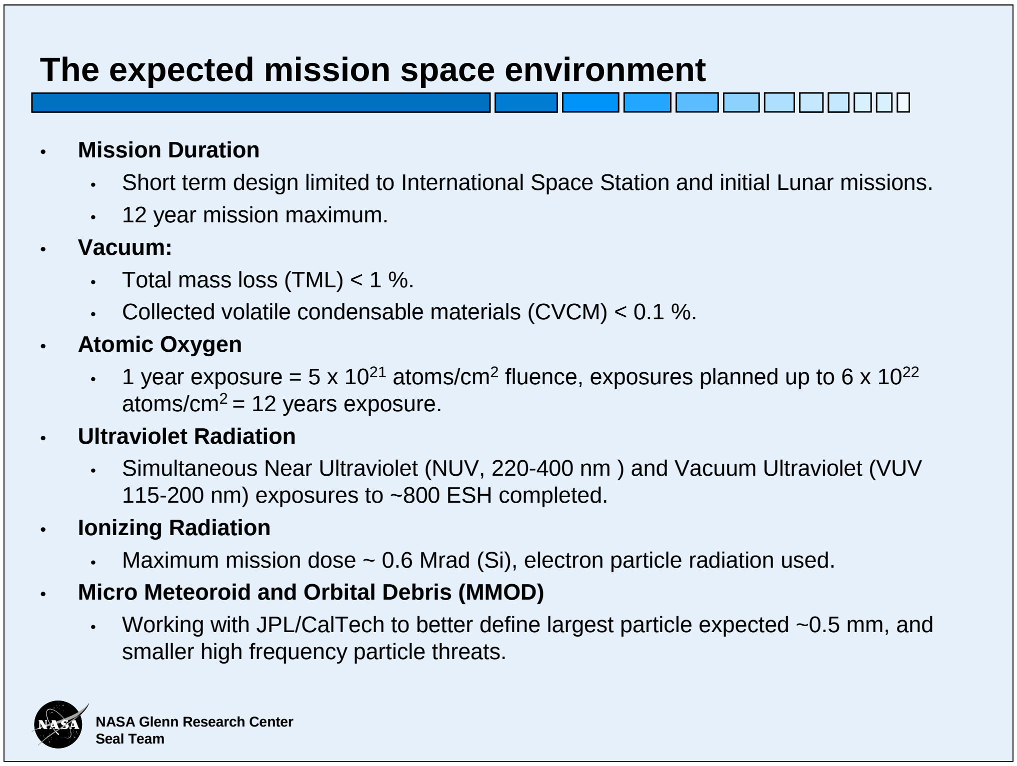
Drawing of the planned CEV docking with Space Station; LIDS enables the coupling of the two together; the elastomer of the LIDS primary seal stops air from leaking out after docking.



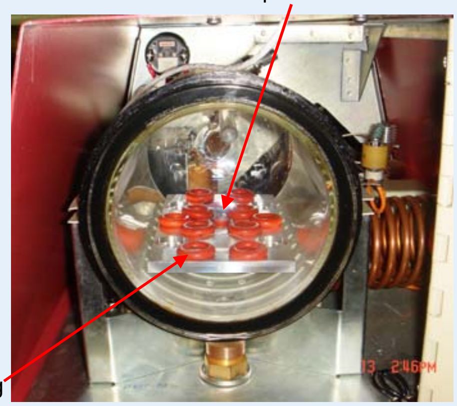
While in space, the LIDS seal will be exposed to vacuum, atomic oxygen, radiations, and solid high velocity projectiles of various forms (MMOD). The amounts of these exposures are highly dependent on the flight path of the particular mission. A worst case exposure would be 15 years, but a trip to ISS, or even to the Moon would be much less. We are using the “Constellation Program Design Specification for Natural Environment” CXP-00102, as our primary source for mission exposures. The effects of vacuum are examined throughout testing, since AO and UV exposures are done with vacuum imposed. UV testing takes the longest; testing out to 1000 hours of equivalent sun hours (ESH) are underway, with accommodations to test longer if needed. MMOD testing employs significant mission flight path analysis and specialized testing. Arrangements for this are underway with facilities at NASA Johnson/CalTech and NASA Johnson/White Sands being employed.

Long-Term Atomic Oxygen (AO) Exposure Facility

Long-term exposure facility:

- Facility used to expose seal materials to oxygen for long periods of time.
- Exposure is isotropic, bathing the specimens in AO, exposing all surfaces.

Kapton witness



2-309 size o-ring

Photo of seal test specimens in the reaction chamber in the SPI Plasma Prep II

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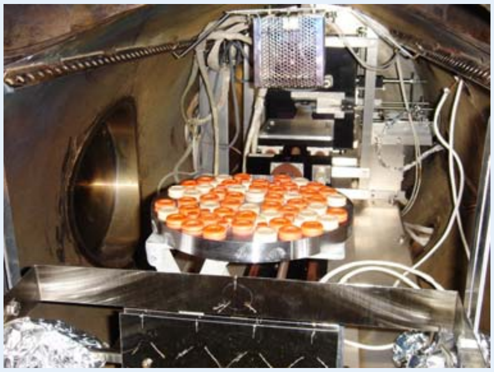
Two SPI Supplies Plasma Prep II facilities operated on air were used to provide the isotropic atomic oxygen arrival. The facilities use radio frequency (RF) (13.56 MHz) to create a discharge between two electrodes which surround a glass reaction chamber. A thermal plasma is produced which is at an energy of about 0.1 eV. Typical vacuum chamber pressure during operation was 16-27 Pa (120-200 mTorr). Temperature measured in past experiments was 65ºC. The two facilities were operated in parallel. One contained an aluminum machined sample tray containing the Parker-Hannifin S0383-70 seal samples and the other contained a similar tray with the Parker-Hannifin S0899-50 seal samples. Each tray had its own polyimide Kapton fluence witness and a sapphire window (2.54 cm diameter) for a contamination witness. Fluences resulting from exposures of S0-899-50 were estimated from Kapton witness coupons exposed alone in a rate test prior to the exposure; this was done because during exposure of S0-899-50 material, contamination of the Kapton witness resulted in erroneous erosion yields.

Shorter term Atomic Oxygen Exposures

- Facility used to expose materials to atomic oxygen for shorter periods.
- Directed beam only exposes top surfaces of specimens to AO.
- Five Kapton fluence witnesses are used with an erosion yield of $3x10^{-24}$ cm^3/atom.



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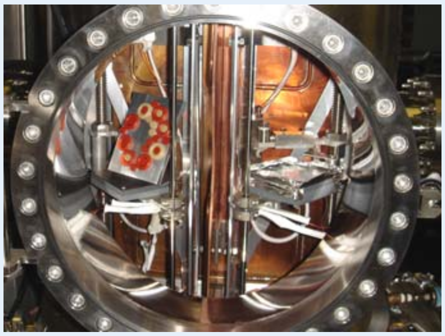
The atomic oxygen directed beam facility uses an Electron Cyclotron Resonance Plasma Source from Applied Science and Technology Inc. (ASTeX) operated on pure oxygen to generate a directed thermal energy beam of atomic oxygen with less than 1% ions at energies of typically 15-18 eV. The source operates at microwave energy (2.45GHz, 1000 W) and uses two large electromagnets for both dissociation of oxygen through electron collision and for beam focusing. The vacuum chamber used for exposure is 71 cm in diameter by 1.71 m long. Pumping is provided by a diffusion pump, mechanical pump and roots type blower that operate on Fomblin (perfluorinated polyether) oil. The base pressure of the vacuum chamber is typically 2e-6 torr to 5e-5 torr, but during operation can range from 2e-4 to 8e-4 torr depending on the oxygen gas flow rate. In addition to producing atomic oxygen, the source also produces VUV radiation at 130 nm at an intensity of approximately 150 suns. Seal samples were installed into recessed grooves cut into a circular plate that was mounted in the facility for exposure. Five polyimide Kapton fluence witness samples were also included on the plate to provide information on the atomic oxygen dose as well as the spatial distribution.

Ultraviolet Radiation Exposures

- VUV Deuterium Lamp (115-200 nm).
- NUV Hg-Xe Arc Lamp (220-400 nm).
- Cryopump vacuum chamber (5 x 10^{-6} torr).
- Seal samples exposed to after AO exposure.



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The Vacuum Ultraviolet (VUV)/Near Ultraviolet (NUV) exposure facility uses a cryogenic vacuum pumping system and VUV and NUV light beams simultaneously. The light source for VUV exposure was a 30-watt deuterium lamp with a magnesium fluoride end-window (Hamamatsu model L7293) which provided a lower cut-off wavelength of 115 nm. Calibration was conducted in vacuum using a cesium iodide (CsI) phototube sensitive in the 115-200 nm wavelength band. The light source for NUV exposure was a 500-watt mercury (xenon) arc source (Oriel Model 66142) which provided NUV of wavelengths in the 220-400 nm range. This NUV source was calibrated before and after each exposure using a pyroelectric detector system (Oriel Model 70362) and a 260 nm narrow bandpass filter. The ratio of lamp intensity compared to the sun’s air mass zero intensity in the same wavelength range is referred to as “equivalent suns”. Equivalent space exposure, referred to as “equivalent sun hours,” is obtained by multiplying the number of test hours by “equivalent suns” for the NUV and the VUV wavelength ranges, 220-400 nm and 115-200 nm, respectively. The NUV and VUV exposures are not uniform over the plate thus exposures are mapped across the plate and the exposure of each specimen tracked. A bright spot located near the center of the plate is avoided. For each test, prior to exposure, all samples were installed in the facility and the chamber was brought to high vacuum for approximately 24 hours to achieve an operating pressure of approximately 5x10-6 torr prior to commencing NUV/VUV exposure.

Ionizing Radiation Exposures

- E-Beam Services in Lebanon Ohio, 150 kW DC Electron Beam Accelerator.
- 4.5 MeV electrons.
- Does of 0.45, 0.9, and 1.3 Mrad (Si).
- 92 Parker specimens exposed, 6 Kirkhill specimens.
- Specimens exposed through entire thickness.

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Particle radiation exposures where done at E-Beam Services in Lebanon Ohio using a 150 kW DC Electron Beam Accelerator which produced 4.5 MeV electrons and a dose of 0.5 Mrad (water) per pass. Both of the Parker elastomers were exposed to 0.5, 1.0 and 1.5 Mrad (water) exposures. No Kirkhill o-rings were available at the time exposures were done. The radiation provided by E-Beam Services is electrons and exposures are reported in units of Mrad (water). We expect this source to give an indication of damage from particle sources in space, even though most solar energetic particles are protons, because damage is primarily determined by energy absorbed and by penetration of the radiation. Sufficiently high fluences were used so that equivalent energy was absorbed and thus hopefully damage equivalent to proton particles. Indications are that below surface doses were slightly higher than noted surface doses due to secondary bremsstrahlung radiations. The approximate conversion of rad dose in Si to rad dose in water in this case, based on stopping powers only, is ~0.9 rad(Si)/rad(water). Thus our three dose levels were 0.45, 0.9, and 1.3 Mrad (Si). Specimens were secured on an aluminum plate and the plates placed in nitrogen filled bags and sealed prior to exposures. Temperature maximum during electron radiation exposures was about 41 oC.

MMOD Test Facilities

- NASA White Sands Test Facility and NASA Johnson Space Center
    - Karen Rodriguez POC

- California Institute of Technology Pasadena, CA and JPL
    - Ares Rosakis POC at Caltech.
    - Virendra Sarohia JPL-Caltech liaison.

	Caltech	White Sands
Max Velocity	10.5 km/s	7.5 km/s
Particle Size	~0.1 to 2.0 mm	~0.05 to 3.6 mm
Success Rate	~99%	80 to 65 %
Number of Particles per shot	1 to 6	1
Analysis Support	Extensive	Good

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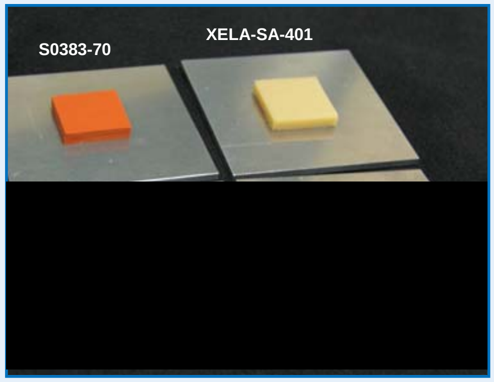
MMOD Test Specimens (Phase I)

Six test specimens:

- Parker S0383-70
- Kirkhill XELA-SA-401
- Ceramic SiC 0.125 inch thick.
- SS plate (0.125 inch thick).

Impacted with 0.5 mm stainless steel particle at 7.5 km/sec.

Elastomer samples were glued onto 3"x3"x1/8" thick Al 7075 plates.



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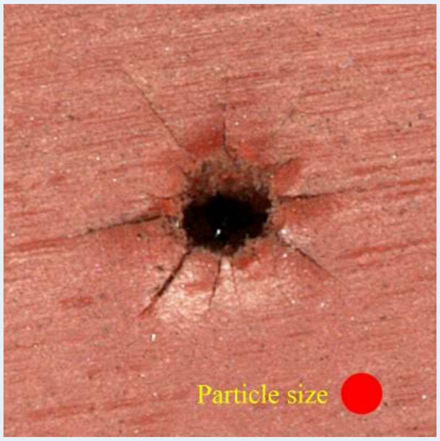
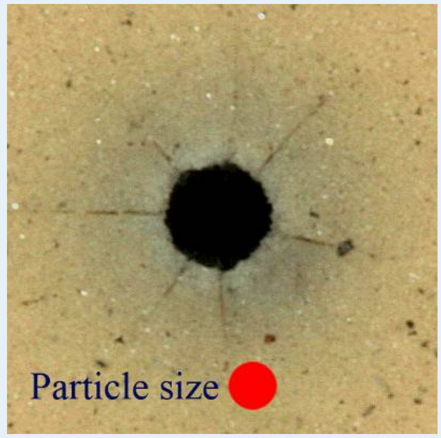
MMOD Test Results

Projectile: Stainless Steel, sphere 0.5 mm dia., 7.5 km/s



Parker S0383-70



Kirkhill XELA-SA-401

- 0.5 mm projectile damages a 5 mm diameter area, 5 mm deep.

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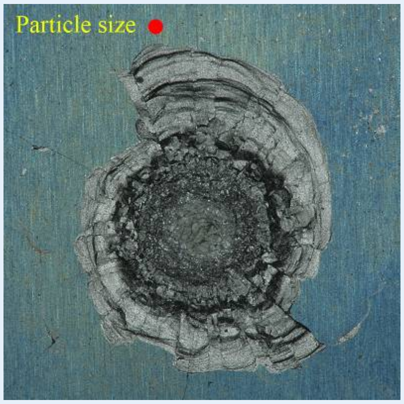
The photographs show the impact craters caused by the 0.5 mm, 7.5 km/s, stainless steel projectile, simulating an MMOD strike. The Parker material had raised edges around the impact crater. The ELA specimen was analyzed via a Computed Tomography (CT) scan to measure the internal damage. The CT scan revealed that the particle left an impact crater of depth 0.165 inches into the 0.200 inch thick target, although it was also evident that particle fragments had penetrated deeper without removing material.

MMOD Test Results

Projectile: Stainless Steel, sphere 0.5 mm dia., 7.5 km/s



SiC

Stainless Steel

- Huge area of the SiC plate damaged (10 mm +)
- Highly raised edges in the Stainless Steel, 3 mm diameter.

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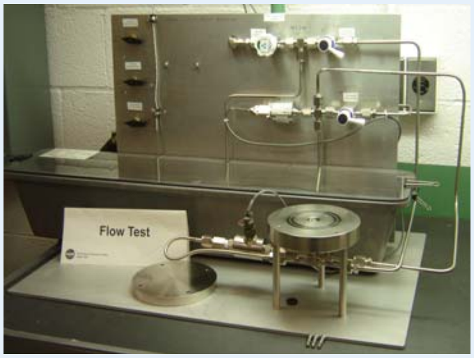
This photographs show the damage caused by the 0.5 mm steel projectile. Deep, long cracks radiated from the crater in the SiC plate. The edges of the crater in the stainless steel were highly raised.

Small Scale Flow Test Fixture

- Quantifies leakage flow past 2-309 size o-ring seal specimens.
- Test conditions
  - 25% O-ring compression.
  - Seal against flat plate.
  - P_{HIGH} = 14.7 psia.
  - P_{LOW} = 0.0 psia.
- Specimen are connected to a leak decay system to accurately quantify losses.
- Data processing then scales up the leak to estimate the primary LIDS seal leakage.



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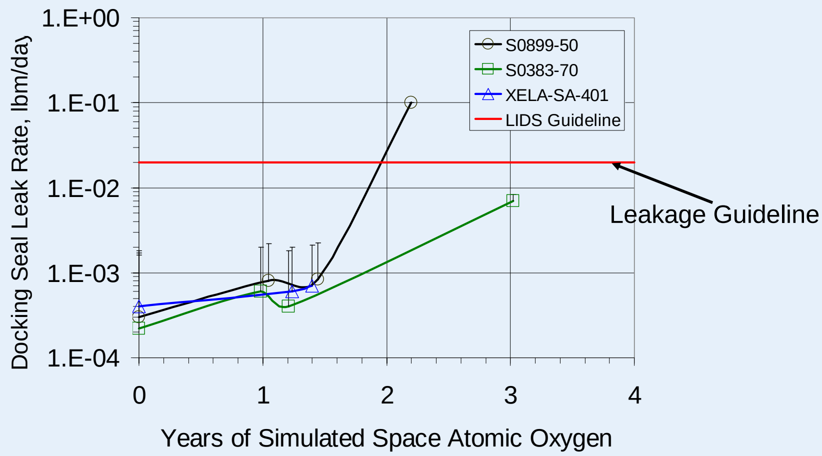
Leak Flow Test Results



• S0899-50 exceeds allowable leak rate after 2 yr AO.

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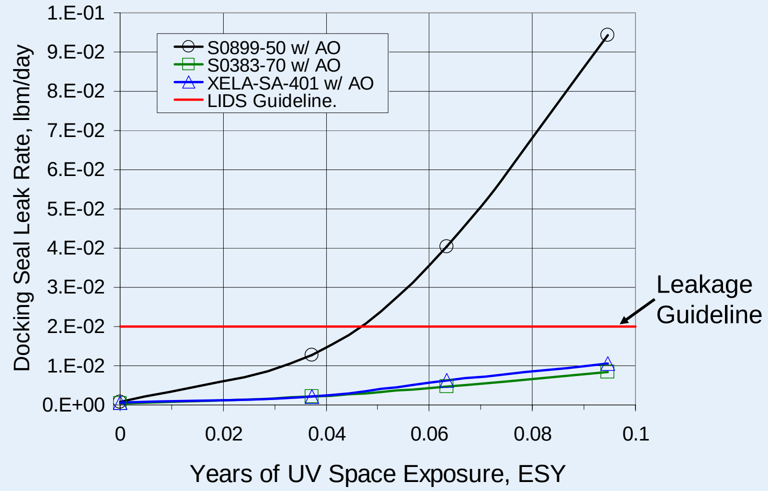
Shown in this plot is the leak rate measured from our 2-309 o-rings scaled up to estimate the leakage from the full ~54 inch (137 cm) diameter LIDS seal. This leak rate is for a single seal. Present designs use a double seal, thus these leak rates are worst case scenarios after a full failure of one of the seals. As received leakage is shown by values at zero years of AO exposure. The red line indicates the maximum leak rate presently sought for the LIDS seal; after 2 years of exposure the Parker S0-899-50 material fails by exceeding this maximum. Atomic oxygen reacts with Si in these silicone based elastomers, forming glassy SiO_2 phases on exposed surfaces. Exposed surfaces become glossy, harder, and less sticky (for example, dust does not collect on them as much).

Leak Rate Results after AO + UV exposures



- S0899-50 fails after 1.2 yr AO + 400 ESH.
- S0383-70 and XELA-SA-401 ok up to 1.2 yr AO + 1700 ESH.

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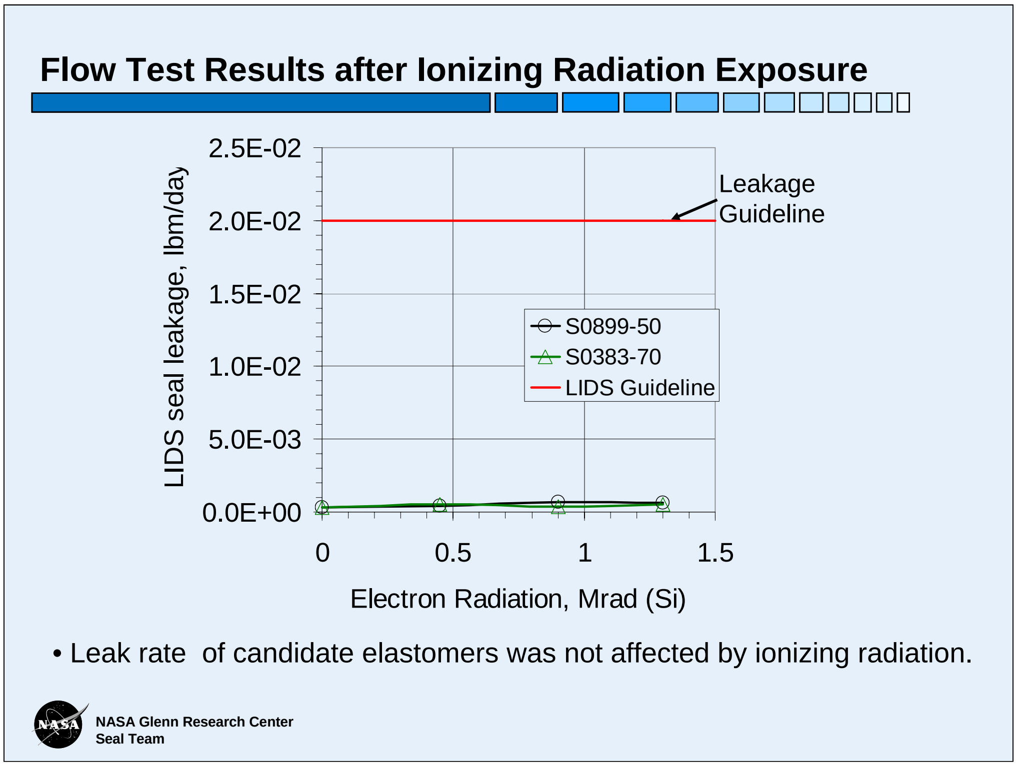
Shown in this plot is the leak rate measured from our 2-309 o-rings scaled up to estimate the leakage from the full ~54 inch (137 cm) diameter LIDS seal. This leak rate is for a single seal. Present designs use a double seal, thus these leak rates are worst case scenarios after a full failure of one of the seals. All specimens in this group were exposed to a fluence of 5.77 x 10^{21} atoms/cm^2 atomic oxygen (AO) prior to exposure to the various levels of ultraviolet (UV) radiation. The red line indicates the maximum leak rate presently sought for the LIDS seal; after the simulated space exposure of about 1.2 years AO and 0.05 ESY (equivalent Sun year) of UV radiation, the Parker S0-899-50 material fails by exceeding the maximum allowable leak rate of 0.02 lbm/day. The estimated error in the measured leakage was +/- 0.0014 lbm/day at leak rates below 0.02 lbm/day; at higher leak rates uncertainties were about +/- 10%.

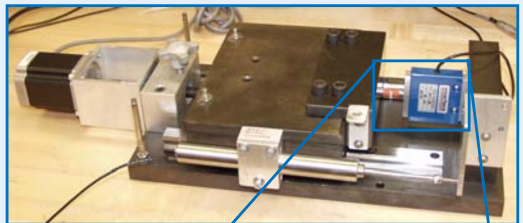


The plot shows the abilities of the Parker elastomers to seal are not significantly effected by expected mission doses of particle radiation. Leak measurement uncertainty was +/- 1.4 x 10^{-3} lbm/day.

Particle radiation exposures where done at E-Beam Services in Lebanon Ohio using a 150 kW DC Electron Beam Accelerator which produced 4.5 MeV electrons and a dose of 0.5 Mrad (water) per pass. Both of the Parker elastomers were exposed to 0.5, 1.0 and 1.5 Mrad (water) exposures. No Kirkhill o-rings were available at the time exposures were done. Sufficiently high fluences were used so that equivalent energy was absorbed and thus hopefully damage equivalent to proton particles. Indications are that below surface doses were slightly higher than noted surface doses due to secondary bremsstrahlung radiations. The approximate conversion of rad dose in Si to rad dose in water in this case, based on stopping powers only, is ~0.9 rad(Si)/rad(water). Thus our three dose levels were 0.45, 0.9, and 1.3 Mrad (Si). Specimens were secured on an aluminum plate and the plates placed in nitrogen filled bags and sealed prior to exposures.

Adhesion Test Fixture

- Quantifies adhesion between specimens after 25% compression for 1, 2, 4, 8, 16, and 24 hours.
- Specimens: elastomer cylinders
  - 0.953 cm (0.375 in.) OD.
  - 0.533 cm (0.210 in.) thick.



Photograph of an adhesion test in progress showing the deformation before separation (left).

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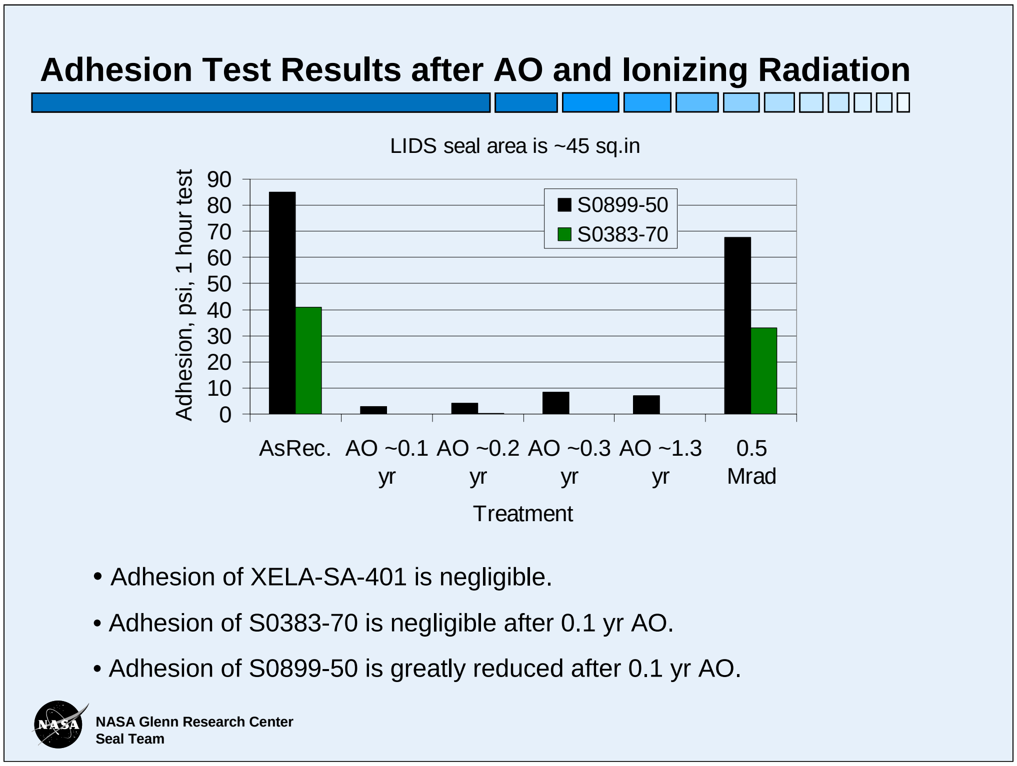

Adhesion test results for Parker-Hannifin S0-8990-50 and S0-383-70 in the as received condition and after exposure to electron radiation and various amounts of atomic oxygen. As received adhesion was negligible for the Kirkhill elastomer ELS-SA-401. Adhesion for S0-383-70 after AO was also essentially zero. The surface area of the LIDS seal is approximately 45 in.^{2}, thus if adhesion between the seals was 10 psi, it would require a force of about 450 lb to get them apart. The variability or scatter among like test was about +/- 20%.

Compression Set Test Fixture

- Quantifies permanent deformation after specimen has been compressed for extended periods of time, 70 hr.
- Testing per ASTM Standards D395 (Test Method B) and D1414.
- Specimen are 2-309 size o-rings 2.11 cm (0.832 in) OD, 0.533 cm (0.210 in.) cord diameter.
- Test conditions 25% Compression, 70 hr. at room temperature, unlubricated.
- Result is the median of three samples.

Compression set test fixture

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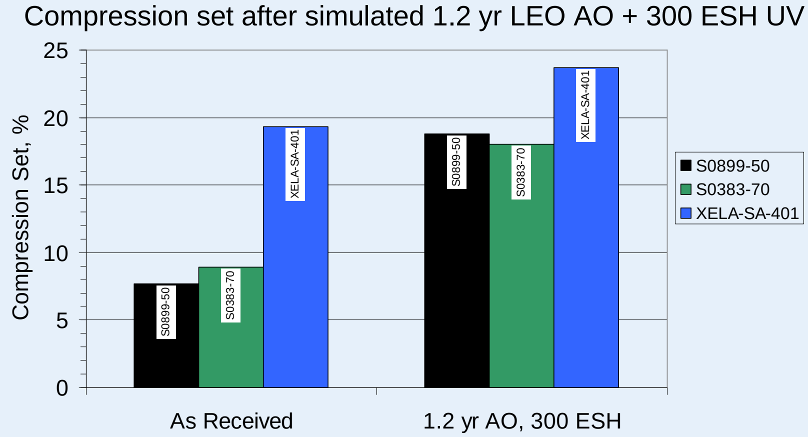
Photograph of the stainless steel plates used to test the compression set of LIDS candidate elastomers. The plates have a diameter of 35.6 cm.

Compression Set Test Results



- Compression set largely unaffected by AO or ionizing radiation alone.
- Compression set significantly increased due to UV exposure.

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Compression set measurements are somewhat artistic. Some of the data was also gathered by different people which did not contribute positively to measurement consistency. In general, scatter and uncertainties in compression set measurements resulted in an estimated accuracy of between +/-10 to +/-30% depending on the particular group and the number of measurements made to date (to be clear, for example, a compression set of 10. +/-2. % was typical). This plot shows the compression set of the candidate materials in the as received conditions, and after a combined exposure of about 1.2 years atomic oxygen (5.77 x10^{21} atoms/cm^2) plus about 300 equivalent sun hours of ultraviolet radiation in the NUV and VUV wavelength range (~100nm to 400 nm). This exposure increased compression set for all three of our candidate seal materials.

Conclusions

- Environmental exposures are highly dependent on mission/flight path.

Vacuum:

- All three elastomers meet mass loss and condensation requirements.

Atomic Oxygen:

- Parker's S0899-50 exceeded the maximum allowable leak rate after 2 yrs. of AO exposure; data indicates S0383-70 will similarly fail after 4 yrs. AO (fluence = 2x 10^{22} atoms/cm^2).
- Adhesion for XELA-SA-401 was negligible; Adhesion for S0383-70 was negligible after small amounts of AO; Adhesion of S0899-50 was deceased to about 5 psi after 0.1 yr AO.
- AO by itself did not influence compression set in these elastomers.

Ultraviolet Radiation (110 to 400 nm)

- Ultraviolet exposure caused increases in leakage. S0899-50 failed after about 400 ESH of UV + 1.2 yr AO exposure. If current trends continue, S0383-70 and XELA-SA-401 will exceed the maximum leak rate of 0.02 lbm/day after about 1800 ESH + 1.2 yr AO.

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Conclusions

UV (continued)

- AO with UV caused the compression set of XELA-SA-401 to increase by about 20%, and a doubling of compression set for the Parker materials.

Ionizing Radiation

- The elastomers are not significantly effected by the expected levels of Ionizing Radiation.

MicroMeteoroid Orbital Debris (MMOD)

- A projectile of 0.5 mm diameter damaged areas about 10 times that diameter, boring deep (5 mm) into the specimens.

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Future Work

- Finishing planned AO, UV, and particle radiation exposures.
- Perform extended UV exposures.
- Commence detailed MMOD studies, low frequency larger particles and high frequency smaller particles with leakage testing.

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