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Investigated Leak Rates of AS5202 Port K-Port Seals Utilizing Helium Mass Spectrometry

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ABSTRACT

AS5202 port seals provide sealing for a wide range of fluids in which a significant amount are liquids with some in the gaseous phase. The amount of compression of a standard seal geometry (O-ring, C-ring etc.) can often be attributed to its ability to create a seal up to a critical value of displacement. This relationship has been well tested within the respective metallic seal families except for k-port seals. This study aims to test this relationship of compression to leak rate within the k-port seal family to further the understanding of how these seals behave in different operational environments. K-port seals of -04 and -16 sizes and in various base material and coating combinations were compressed to different values and were tested using helium mass spectrometry and gaseous ultra-high purity helium. The seals were then imaged post testing to characterize the seal tracks created by each compression test. It was shown that most of the k-port seal configurations exhibit far better leak performance than recommendations within available AS5202 port standard guidance and existing metallic k-port seal guidance.

BACKGROUND

K-port seals are a class of metallic sealing options that are often used within AS5202-AS933 paired hardware.[1,2] These seals are based on the legacy MC252 specification[3] (Figure 1). This family of seal designs consist of multiple contacting seal tracks (where the seal resists flow): the two legs of the seal (upper and lower), as well as a limiter/gasket type outer seal (secondary seal). These seals although diametrically controlled by the standard ports and fittings they are used in conjunction with, are designed with specific the upper and lower leg geometry that allows for energizing of the seal through system pressure. Nominal dimensions of the seal are included in Table 1. The subject of these tests are the -04 and -16 standard size seals. A schmatic of a cross-section of a k-port seal is included as Figure 2.

This style of port is commonly used within the aerospace and space launch communities. Generally speaking, the main fluid sealed is often some kind of fuel or propellant, usually in the liquid phase. Typical liquid phase fuels/fluids include: liquid oxygen (LOX), liquid nitrogen, liquid methane, liquid hydrogen, and RP-1 (kerosene based fuel).

Figure 1: Diagram of a Standard K-port Seal[4]

These seals are also employed closer to combustion of the system causing this environment to include gas/liquid phases to be present together or contain a mixture of high temperature air and fuel. There is little literature/data on how these seals behave within a gaseous environment. General guidance suggests that these seals are viable for gaseous use to a value of about bubble leak performance requirements (or roughly 1×10^{-4} atm*cc/s). This suggestion, however, does not include actual testing of the seals it has been developed over time and system design in the community of use. To increase reliability of system with gaseous phase (or dual phase) fuel, characterization of this seal family is paramount.

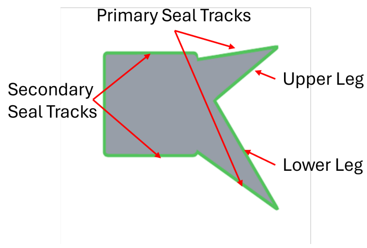

Figure 2: Illustration of a Standard K-port Seal with PTFE coating

Due to the large variety of fuel/fluids, temperature and pressures within any given environment, these seals have a wide variety of materials and coatings that are used for mechanical/temperature stability as well as environmental resistance. Generally, designs with a polytetrafluoroethylene (PTFE) coatings are used within cryogenic applications.[5] Other seal top coats including Gold and sometimes even Nickel plating have been used in hotter applications closer to combustion. Considerations and design criteria vary vastly in system design and usage fluid/fuel, temperature, as well as operating pressures (high performance being over 8,000 psi).[5,6] Common base seal materials used within the k-port family include stainless steel alloy 304, alloy A286 hardened Stainless Steel, Inconel alloy 718 and X-750. These seals are currently suggested/rated to a maximum internal pressure of 3,500 psi per AS5202 specification for usage, but are defined by the surrounding hardware limits, not the seal itself.[2,7]

Regarding static metal seals, most seal families (O-ring, C-ring, spring energized, etc.) work on the basis that a large load is applied to the seal to plastically deform either the contact surface of the seal itself or the outer coating of the seal being used. The outer most material of the seal is then able to flow into any imperfections/surface roughness found on the mating hardware allowing for a more leak tight seal to form.[8] A lower strength material is often added to the outside of a high strength metal based seal to allow for higher degrees of deformation on the outer layer of the seal, increasing the sealing performance, with some seals reaching leak rates of 1×10^{-9} atm*cc/s or better.

Table 1: Nominal Dimensions of -04 and -16 K-port Seals[1,2]

Dimension	-04	-16
Outer Diameter (in)	0.688	1.656
Inner Diameter (in)	0.451	1.330
Leg Height (in)	0.122	0.139
Limiter Height (in)	0.62	0.62

EXPERIMENTAL PROCEDURE

This study consisted of physically testing a variety of sizes, base materials and coatings on k-port seals standardized for use within AS5202/933 standard port connection geometry.[1,2] For statistical relevance five (5) seals were tested for each material combination condition.

TEST SEAL MATERIALS

Included in Table 2 are the specific combinations of seal base materials and coatings tested in this study. There are two different seal base materials: Alloy X-750 per AMS 5667 and stainless steel (SS) alloy 304 per AMS 5639. The X-750 was precipitation hardened per AMS 5667 prior to machining. Gold coating was completed on both materials to a nominal thickness of 0.0005 inches per MIL-G-45204 Type III Grade A Class 4. PTFE was coated on both base materials per AMS 2515 to a nominal thickness of 0.002 inches. Nickel plating was completed per AMS 2424 with a nominal thickness of 0.0005-0.001 inches on the X-750 base materials only due to the higher durability of nickel and increased anticipated load requirements of the test seals. The parts were cleaned and inspected after machining and coating processes and sealing surfaces were ensured to be free of nicks, scratches and other imperfections that would impair seal function or potentially impact leak rate results.

Table 2: Seal Sample Base Alloy and Coating Material Combinations (-04 and -16 size)

Seal Sample	Base Material	Coating
Sample A	Alloy X750	PTFE
Sample B	Alloy X750	Gold
Sample C	Alloy X750	Nickel
Sample D	SS304	PTFE
Sample E	SS304	Gold

TESTING PROCEDURES

Loading Protocol

For physical loading of the seals in each gland, an Instron 8802 servo-hydraulic load frame was utilized (with load capacity up to 250kN, or 56,000lbf). The -04 seals were compressed to a nominal load of 2,875 lbf; the -16 seals were compressed to a nominal load of 6,600 lbf. The loading protocol for leak testing was as follows: compress seal to nominal load, hold at position so that load value could be achieved and allow for stress relaxation of the seal, conduct leak test with mass spectrometry, and unload after leak testing values stabilize and testing is complete. This protocol was followed to create a more realistic loading condition as those from legacy seal designs. Due to stress relaxation of the seals and the variation in manufacturing tolerances, the load and unload portions of the load vs displacement curves presented in a later section do not exactly match at the nominal load of each seal. This was expected due to the large variation of seal tolerances on the product itself. On a few of the tests, due to the position hold method of loading, an excursion above the nominal load was experienced by some of the seals. It was again not unexpected, happened throughout leak testing, and did not invalidate any test conditions.

Mass Spectrometer Protocol

Leak testing protocol was modelled after the hood technique outlined in FED-STD-151 B.[9] The operators of the test cases here have minimum qualification of LT1 per SNT-TC-1A guidelines for qualified operators.[10] This testing included the use of the following equipment: a helium mass spectrometer leak detector (MSLD), calibrated leak (1.72×10^{-10} atm*cc/s), extensometer/LVDT, katharometer, temperature sensors, pressure sensors, test fixture manufactured to AS5202 geometry, and an ultra-high purity helium source (UHP helium). The calibrated leak is placed as close as possible to the test tooling and is compensated for time and temperature differences from those at which it was calibrated. The minimum detectable value for the Pffifer Vacuum ASM 340 is 5×10^{-12} $atm \times cc \div s$. This is the minimum leak rate that the MSLD can detect given ideal conditions. The seals in the study were tested with helium being injected into the inner diameter of the seal and test hardware (at 14.7 psia), with the outside of the seal being held under vacuum conditions by the MSLD. A diagram of the experimental setup is included in Figure 3. When reporting MSLD data, it is often that the leak rate of the part in question is lower than either the minimum detectable limit (5×10^{-12}) or the test procedure sensitivity. For data presented in this study, a $<$ sign will be included to indicate that the leak rate is lower than the value presented.

Test Procedure (refer to Figure 3):

1. Ensure MSLD is in standby, clean test fixture and seals with alcohol based solvent
2. Ensure all valves (V1, V2 and V3) are shut
3. Load seal into test tooling, place test fixture into the load frame
4. Connect MSLD to test fixture
5. Use the Instron to compress seal to nominal height/load requirement
6. Initiate test mode on MSLD and open V1
7. Record calibration leak temperature (to calculate corrected calibration leak rate) and open V2
8. Record the value upon visual MSLD stabilization and shut V2
9. Allow signal stabilization and record this value as background levels
10. Open V3 and inject helium into the ID of the seal to the required pressure. Measure and record helium concentration (using the kartharometer) and atmospheric pressure
11. Once the signal is stable on MSLD, record leak rate
12. Open V2, allow stabilization and record this value
13. Using previous values, calculate correction factors and a corrected leakage rate per ASME BPVC Sect. V Art. 10[11]
14. Remove load, take hardware out of the Instron, and remove tested seal for imaging

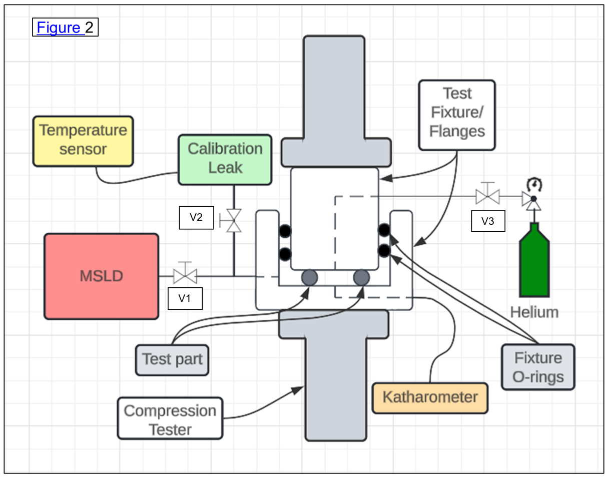

Figure 3: Diagram of the Leak Testing Setup

RESULTS AND DISCUSSION

Load vs Deflection

Load vs deflection curves were created for each test condition and help ensure that full compression of the seal was achieved (Figures 4 and 5) Each seal in both sizes reached full compression. This is indicated by the change in slope near 0.0014in of displacement, and also indicated secondary seal engagement. Each size of seal achieved full compression within 0.002in of each of the respective samples. This is most likely due to differences in seal geometry tolerances as well as coating thickness tolerances. The PTFE coated seals were observed to have later full compression (more displacement) than the metal coated seals, and was expected due to the higher initial thickness of material in comparison to gold and nickel plating. In addition to PTFE normally being coated at a much higher material thickness compared to the metallic coatings, PTFE is also considerably lower hardness/stiffness. This should result in the seal needing more displacement to reach the full compression load values. During decompression of the seals, springback of the seal (within the seal legs) is observed. This resilience is what allows metallic seals to continue to provide high performing sealing as surrounding materials expand and contract due to thermal expansion in service conditions. All seals exhibit some degree of resiliency (at least 0.001in) with X-750 seals showing the largest amount of resiliency. Paired with PTFE (more displacement needed for compression), these seals have the largest amount of resiliency ($\approx 0.0025in$).

During compression of these seals (and most metallic seals), a seal track is formed (where flange and seal materials create a contact pair).[8] A representative image of a -16 gold-coated seal (before and after compression) are included in Figure 6.

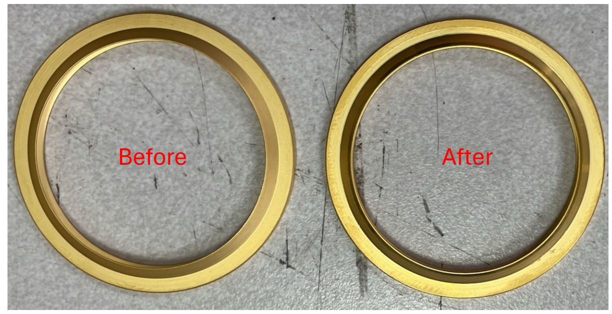

Figure 6: -16 Gold-Coated Seal (Sample B) . (before on the left, after on the right)

The tested seal has a "burnished area" that is indicative of a seal track formed on the upper and lower leg of the seal, as well as on the limiter (secondary seal). The rest of the seals tested in the study had similar "burnished" seal tracks formed due to the presence of plastic deformation of the outer coating layer of the seal upon installation and nominal compression. The nickel-coated seals (Sample C) had the least visually identifiable seal tracks. However, using optical enhancements/microscope they were found to still be present in the tested seals.

Helium Mass Spectrometery Leak Testing

-04 Size

Helium leak rate data is presented in Table 3 for the -04 size seals. Most of the seals tested in the -04 size had leak rates below the minimum detectable limit of the machine or the background helium levels making the test more of a pass/fail experiment, instead of determining an exact leak rate. The SS304 base material with PTFE coating version of the seal measured one of the tests to a leak rate of $3.72 \times 10^{-9} atm * cc/s$. This measured leak rate is still multiple orders of magnitude lower than the expected leak rates found in literature/guidance.[4,12] Within this group, no other PTFE, nickel, or gold coated seals tested had a measurable leak rate above experimental machine/environment tolerance and thus were measured as "passed". Seal tracks were visible on the upper legs of the seal for each coating.

-16 Size

Helium leak rate data for the -16 size seals had similar behavior to the -04 seals. As seen in Table 4, the PTFE and gold coated seals were tested to

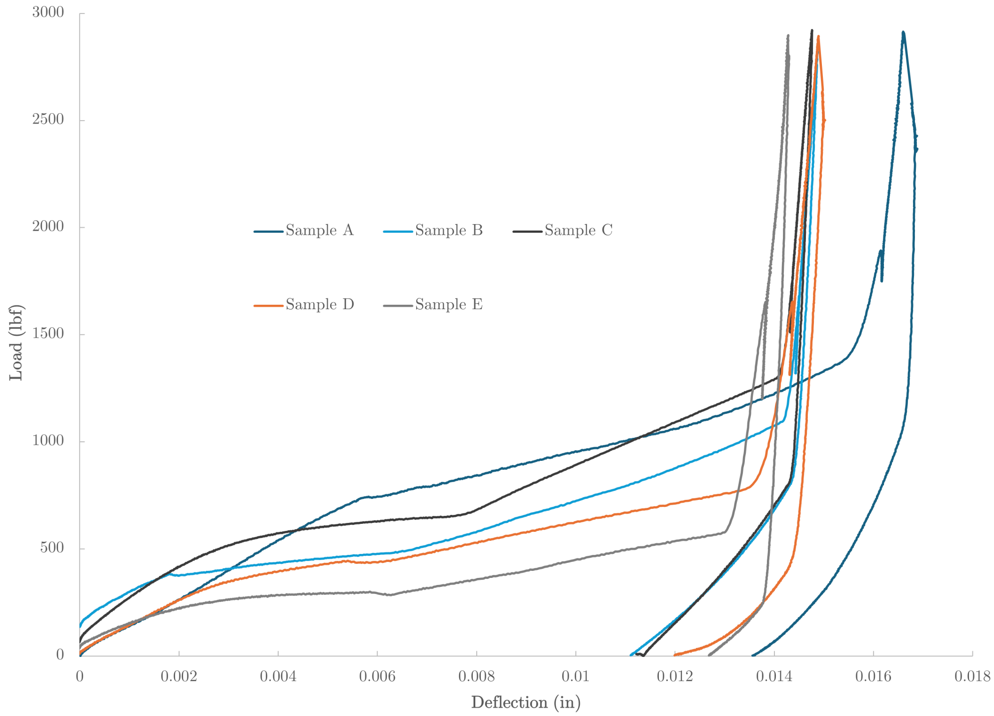

Figure 4: Load vs Deflection Curves for -04 size K-port Seals

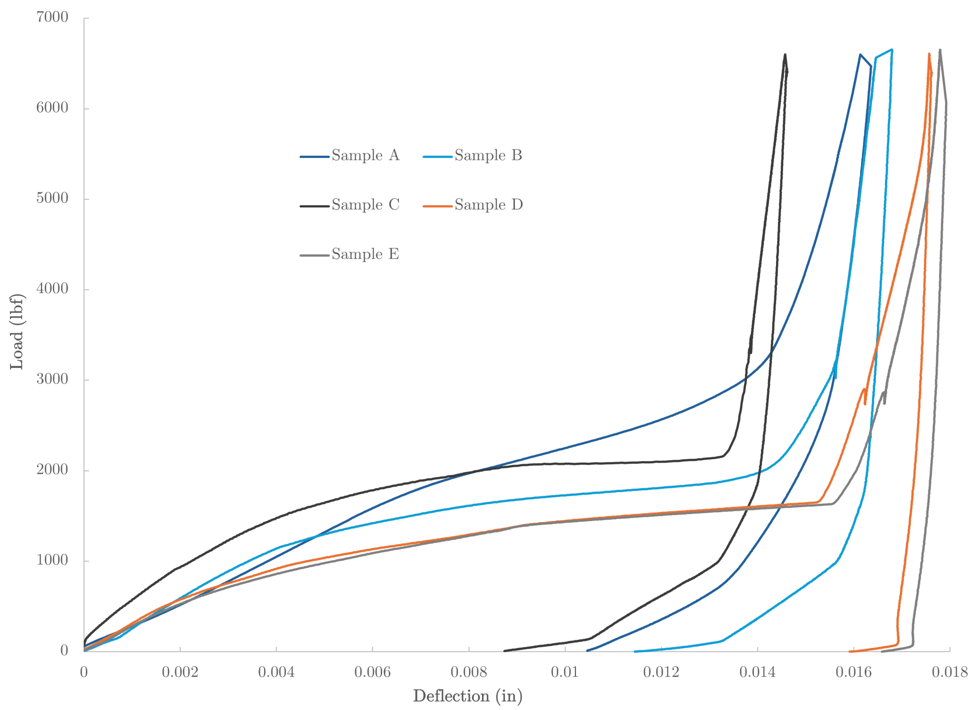

Figure 5: Load vs Deflection Curves for -16 size K-port Seals

Table 3: Helium Leak Rates of -04 Seals

Seal	Helium Leak Rate (atm*cc/sec)				
Sample A	$< 5 \times 10^{-12}$				
Sample B	$< 1.29 \times 10^{-11}$	$< 1.28 \times 10^{-11}$	$< 1.31 \times 10^{-11}$	$< 5 \times 10^{-12}$	$< 1.15 \times 10^{-11}$
Sample C	$< 1.25 \times 10^{-11}$	$< 1.30 \times 10^{-11}$	$< 1.32 \times 10^{-11}$	$< 5 \times 10^{-12}$	$< 1.30 \times 10^{-11}$
Sample D	$< 5 \times 10^{-12}$	$< 5 \times 10^{-12}$	3.79×10^{-9}	$< 1.32 \times 10^{-11}$	$< 1.38 \times 10^{-11}$
Sample E	$< 9.31 \times 10^{-12}$	$< 5 \times 10^{-12}$	$< 1.18 \times 10^{-11}$	$< 1.21 \times 10^{-11}$	$< 1.40 \times 10^{-11}$

Table 4: Helium Leak Rates of -16 Seals

Seal	Helium Leak Rate (atm*cc/sec)				
Sample A	$< 9.31 \times 10^{-12}$	$< 9.51 \times 10^{-12}$	$< 1.18 \times 10^{-11}$	$< 1.21 \times 10^{-11}$	$< 1.40 \times 10^{-11}$
Sample B	$< 1.12 \times 10^{-11}$	$< 5 \times 10^{-12}$	$< 5 \times 10^{-12}$	$< 1.15 \times 10^{-11}$	$< 1.21 \times 10^{-11}$
Sample C	$< 1.38 \times 10^{-11}$	$< 5 \times 10^{-12}$	7.10×10^{-6}	$< 5 \times 10^{-12}$	No Seal
Sample D	$< 5 \times 10^{-12}$	$< 5 \times 10^{-12}$	$< 1.30 \times 10^{-11}$	$< 1.32 \times 10^{-11}$	$< 1.38 \times 10^{-11}$
Sample E	$< 5 \times 10^{-12}$				

all have leak rates below experimental background or minimum detectable limit of the machine. The nickel-coated X-750 seals had one seal tested with a measurable leak rate; however, it also had one that was tested where a seal with a leak rate that was low enough to be measure using this method could not be established. Because the Ni-coated -04 seals all had leak rate values below measurable levels, it can be postulated that there is a critical load value that results in the Ni-coating forming seal low enough to be measured (or known to be less than a value). This may not have been achieved with the larger -16 seals. This would need to be explored within the scope of a separate project.

Conclusions and Future Work

Loading was similar for -04 and -16 seals, with the limiter making contact within a 0.002in tolerance on each seal tested. This was used to confirm that the seals achieved the nominal value of full compression. Resilience in the seals was also observed, with X-750 PTFE-coated seals having the largest amount of springback. This resiliency would be expected to be less at high temperatures due to material yield strength reduction and higher at cryogenic temperatures due to material strength enhancement when compared to standard temperature testing. It would also be postulated that resilience would increase in all service conditions when system pressure is present in the application, but thermal excursion testing and pressurized testing would need to be explored in another experiment.

For the -16 size, all PTFE and gold-coated seals had leak rates below experimental minimum detectable limit/background values. Nickel showed some variability most likely due to differences in hardness and resulting deformation of the coating layer when compared to PTFE and gold. One nickel-coated -16 seal could not form any seal with a leak rate that was low enough to be measure using this method and a second seal that was tested measured a leak rate of approximately $1 \times 10^{-6} atm*cc/s$ magnitude. This is still lower than the guidance found in literature/legacy design data that states values of $1 \times 10^{-4} atm*cc/s$. One PTFE-coated -04 seals that were tested had a measurable leak rate, however, it was in the $1 \times 10^{-9} atm*cc/s$ range, which is many orders less than guidance of legacy designs. All others -04 seals tested measured below experimental minimum detectable limit/test procedure sensitivity.

For future work, it is planned to expand on different loading conditions to determine if/where there is a critical load where each coating consistently provides a seal with a leak rate that was low enough to be measure using this method. It is also planned to add temperature and pressure as variables to test. This will more closely resemble the service life conditions of these seals. A third aspect of the testing yet to be completed has to do with the nature of the hardware and seals in service. These fluid connections are typically threaded connections, and will have some kind of burnishing effect when fully installed, and was not considered for this testing. The seals tested for this work were all tested only in compression, no threaded features were used and was intended to mimic the high pressure custom fittings found in high pressure service conditions

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