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Developing Technologies and Techniques for Additive Manufacturing of Spacesuit Bearings and Seals

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Human exploration beyond low Earth orbit will require increasing self-sufficiency in light of the logistics support challenge. One critical area is in spacesuit maintenance, parts replacement, and eventually in-situ manufacturing. An ongoing project at the University of Maryland (UMd) is exploring additive manufacturing (AM) for space suits, both "hard suits" entirely fabricated from feed stock, and "hard" elements of conventional hybrid suits. The current technology development focus is on the integral structural elements of bearings, seals, and interfaces to the suit envelope. Prior work investigated the feasibility of "printing" full bearings, and led to the realization that current AM techniques are of insufficient precision to allow the fabrication of the bearing balls directly. In this paper, complete bearings were assessed for joint friction under varying loads, and tested to destruction to verify the ability to meet both pressurization and human loads with adequate factors of safety. Seals were fabricated of elastomeric 3D printed materials and tested for sealing performance and friction. Complete suit bearing prototypes consisting of both AM bearings and seals were fabricated and subjected to load tests, as well as tested in the UMd glove box and cycled to determine operating lifetime. Based on these results, the best performing design that met all requirements was selected for the fabrication and test of a complete AX-5-type four-roll elbow module, which was integrated to fabric upper and lower arm segments and terminated with a glove box sealed bearing on the proximal end and a standard glove disconnect on the distal end. This arm segment will be used for human factors evaluations in the UMd glovebox, including quantifying dexterity via a Fitts' law protocol.

Nomenclature

ASTM	=	American Society of Testing and Materials
AX-5	=	Ames Experimental suit 5
EVA	=	Extravehicular activity
CAD	=	Computer Aided Design
CVCM	=	Collected Volatile Condensed Materials
FDM	=	Fused Deposition Modeling
PHASE	=	Printed Hard Arm Space Suit Enhancement
P	=	Pressure
r	=	radius
SLS	=	Selective Laser Sintering
SSL	=	University of Maryland Space Systems Laboratory
t	=	wall thickness
TML	=	Total Mass Loss
σ	=	Stress
σ_{hoop}	=	Hoop stress
σ_{axial}	=	Axial stress

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I. Introduction

The success of human exploration and eventual settlement of Mars will depend partially on the development of a spacesuit that can meet the increased demand of extravehicular activity (EVA) on long-duration missions. Current "soft goods" spacesuits are subject to wear and abrasion, problems that would be compounded due to the increased frequency and duration of EVA for Mars exploration. In the event of damage to spacesuits, repairs would require a stock of replacement parts or the transport of these parts from Earth. Since launch windows to Mars are dictated by 26-month synodic periods, it is important that astronauts develop a substantial level of autonomy. Additionally, a stock of replacement parts would occupy valuable mass and volume on spacecraft. Additive manufacturing (3D printing) of spacesuit replacement parts or entire rigid spacesuits may present a unique potential solution to these problems. The use of a hard suit almost entirely created using additive manufacturing techniques would allow for repairs to be made *in situ*, and would decrease the volume required to send and/or store replacement parts and supplies.

This paper presents the continuation of the design and testing of the Printed Hard Arm Spacesuit Enhancement (PHASE) prototype spacesuit arm fabricated using additive manufacturing. Starting with a baseline suit kinematic configuration mirroring that of the NASA AX-5 spacesuit, the primary functional allocations of the suit elements were focused down to structural elements, bearings, and seals. This paper specifically focuses on the development and testing of 3D printed seals, which were integrated into PHASE bearings. Sealed bearings were evaluated for lifetime, friction under loading, and pressure retention. Flexible 3D printed material selected for use in prototype seals were also tested for outgassing.

II. Material Selection

Prototyping materials for seals and bearings were selected based on prior work[1] in tensile testing and pneumatic testing. DuraForm GF, a glass-filled plastic fabricated using a Selective Laser Sintering (SLS) printing process, was initially chosen as the PHASE final prototype material. This material serves as a cheaper analog to Windform XT, a space-rated carbon fiber SLS composite. If 3D printed rigid suits were to be flown, they would be printed using Windform XT or another of the select set of space qualifiable additive manufacturing materials.

Later, DuraForm GF was rejected in favor of another SLS manufactured material, DuraForm PA, a polyamide (nylon) material. Issues with unexpected sizing variation due to material shrinkage in parts printed with DuraForm GF prompted the change. This issue was not observed in parts printed with DuraForm PA. Tensile and pneumatic testing was not conducted with DuraForm PA; however, its tensile strength is more than twice that of DuraForm GF[2,3], and it has also demonstrated pressure retention capability in glovebox tests. Additionally, because this is an SLS fabricated material, it also serves as an appropriate analog to Windform XT.

Sealed bearings created for early trials of preliminary testing in the SSL glovebox were fabricated using Stratasys' standard Polyjet material RGD840 Veroblue. This material was selected as an early prototyping material due to the ease of access to Polyjet printers at the University of Maryland. Though Polyjet Veroblue material was deemed unsuitable as a final prototyping material due to its unpredictable behavior beyond its elastic region, it is suitable for use in early design iterations because it can retain pressure and can be printed with a similar precision to materials printed with SLS. Similar precision between Polyjet and SLS processes is important because bearings must be designed with tight tolerances.

Seals were fabricated using a multi-material blend of Stratasys' flexible Polyjet Tango material and Standard Veroblue Material. Varying the ratio of flexible to rigid material results in varying hardnesses for the rubber-like 3D printed material. We used a ratio resulting in seals with a hardness of Shore70A, similar to commercial Viton seals.

III. Preliminary Pressure Testing and Seal Design

A. Glovebox Test Procedure

Sealed bearings were tested in the Space Systems Laboratory glovebox at the University of Maryland. The purpose of these tests was to determine the sealed bearings' ability to withstand a pressure differential of 4.0 psi, and to qualitatively assess the friction in sealed bearings under pressure loads. A pressure differential of 4.0 psi was chosen because it is the maximum pressure differential achievable in the UMd glovebox. The target operating pressure of the PHASE prototype is 8.3 psi.

For these tests, we designed a modified version of our standard PHASE bearings that were sized for the glovebox opening and had a solid inner race. **Figure 1** shows this test set up in the glovebox with our first design iteration. The modified bearing was fitted into a circular opening in the glovebox, and the glovebox was pumped down to create a maximum pressure differential of 4.0 psi.

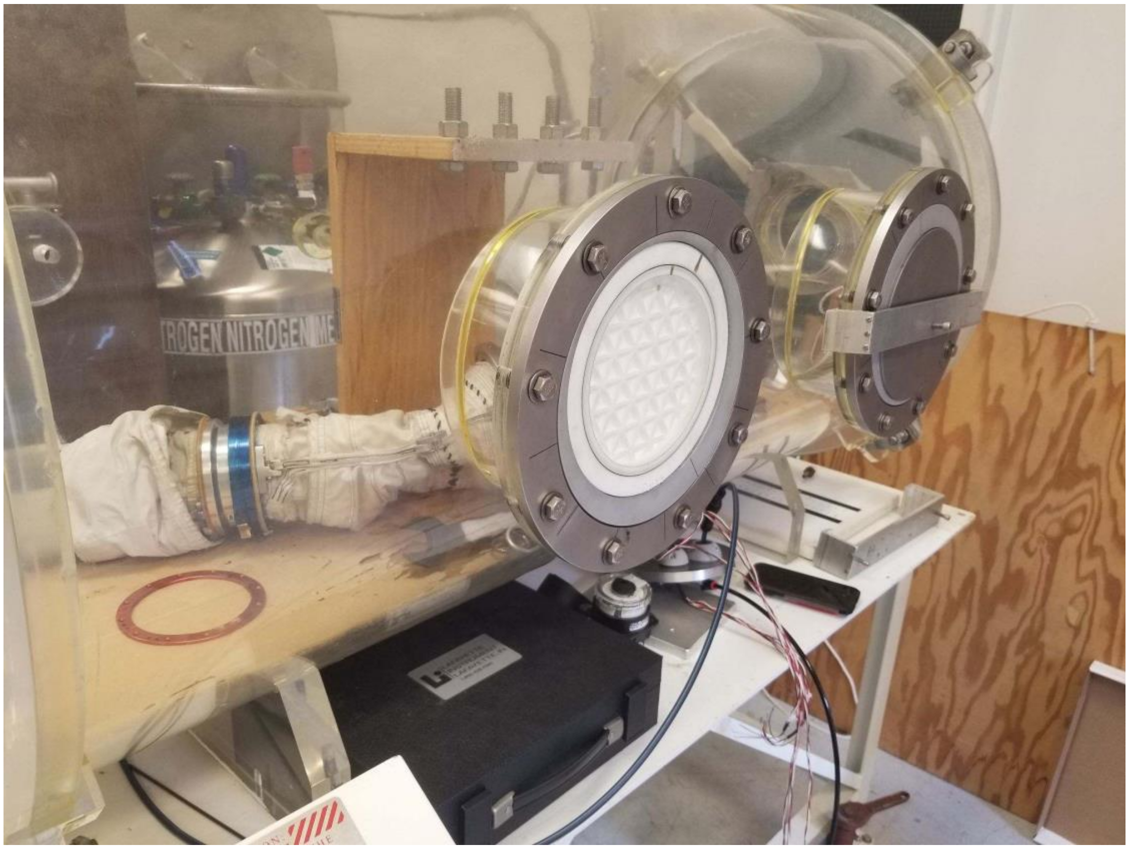
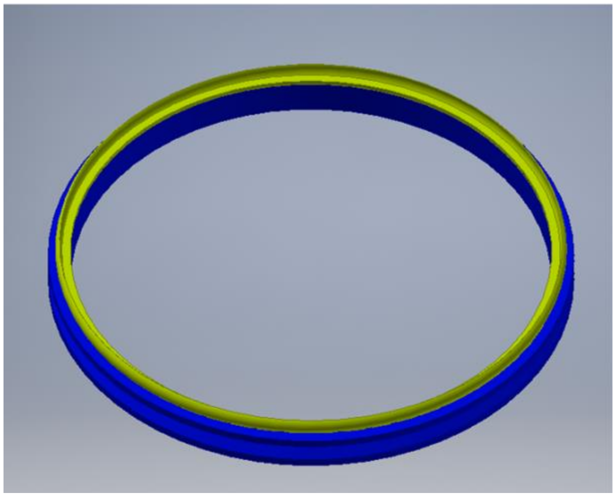


Figure 1. Modified bearing fitted into the SSL glovebox for preliminary pressure testing

B. Design Iteration One: Pressure Energized Lip Seal

The first seal design evaluated was a pressure energized lip seal that was directly 3D printed onto the inner bearing race as shown in **Figure 2a** (left) and **Figure 2b** (right). Note that the modified inner race used for glovebox testing Trials 1 and 2 was printed in Stratasys RGD810 Veroclear material, which has similar material properties as Stratasys RGD840 Veroblue material[4].



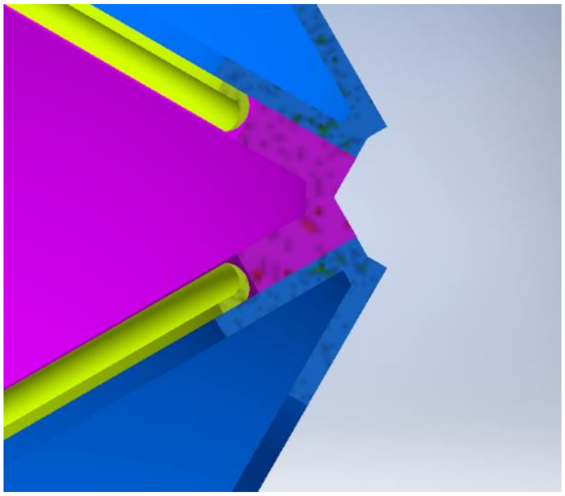


Figure 2a (left). CAD of a PHASE inner race (blue) and pressure energized lip seal (yellow)
Figure 2b (right). CAD cross section of the lip seal (yellow) in a fully assembled prototype. The outer bearing race represented in blue, and the inner bearing race is represented in purple. Note that the actual bearing races are not rendered here

Lip seals have a theoretical single point of contact with the sealing surface which should have minimized friction and been adequate in withstanding a pressure differential. However, glovebox testing revealed major shortcomings of the design. We observed that the contact area between the seal and sealing surface was larger than expected when pressurized, causing unacceptably high friction. Additionally, since the seal was printed directly onto or otherwise permanently attached to the inner race, it could not be replaced independently. If directly printed onto the inner race, it also needed to be fabricated using a process with multi-material capabilities. The precision required for lip seals was also too high to be resolved using currently available printing processes.

Glovebox testing demonstrated that Iteration One, the 3D printed lip seal, was not adequate to retain a pressure differential of 4.0 psi. The results of three glovebox tests conducted with the lip seal design are tabulated in **Table 1a.**

Table 1a. Glovebox Test Results using Design Iteration One

Trial Number	Seal Material/Manufacturing Process and Hardness	Bearing Race Material/Manufacturing Process	Seal Design and Changes	Maximum Pressure Differential (psi)	Notes
1	Stratasys Tango Black FLX (Shore 26-27A)	Stratasys' Standard Polyjet Material RGD840 Veroblue	Lip Seal	2.5	-Seal sucked into gap between races by pressure -Seal was not rigid enough -Material was too soft
2	Stratasys Flexible Digital Material (27A-70A; exact hardness unknown)	Stratasys' Standard Polyjet Material RGD840 Veroblue	Lip Seal -increased material hardness by blending rigid and flexible material -increased lip seal thickness	<1	- Incorrect sizing of seal -Seal did not have contact with sealing surface

3	Stratasys Flexible Digital Material (27A-70A; exact hardness unknown)	Stratasys' Standard Polyjet Material RGD840 Veroblue	Lip Seal -sizing correction: increased seal outer diameter to increase contact between seal and sealing surface	3.0	-too much contact with sealing surface -High friction; difficult to rotate - Bearing races began to pull apart -Inner race failed

The lip seal design experienced various different failure modes in glovebox testing that highlighted several of its disadvantages. After each failed test of this sealed bearing design, we attempted to make small corrective adjustments to the seal.

Test 1 failed due to improper material choice for the seal. We initially chose to fabricate the seal using Stratasys TangoBlack FLX. This rubber-like material was too soft, causing the seal to be overly flexible. As a result, rather than resisting the pressure differential, it was pulled into the gap between the inner and outer bearing races as shown in **Figure 3**.

Figure 3. Lip seal following glovebox test 1. The lip seal was too flexible and was pulled between the inner and outer bearing race by the pressure differential. This prevented the bearing from rotating[1].

After observing this failure mode in Trial 1, we increased the thickness of the seal to improve rigidity and fabricated it using a multi-material blend of Stratasys' Polyjet rigid and flexible material, resulting in a harder rubber-like material. However, the exact hardness of this seal material in Trial 2 and 3 is unknown. This is because the campus printing service used to fabricate the seal for these tests did not record the exact ratio of rigid to flexible material.

Test 2 was unable to withstand any pressure differential due to incorrect sizing of the seal. The diameter of the seal was too small, so it did not achieve an adequate sealing pressure. In Test 3, we attempted to correct the bearing size by increasing the outer diameter of the lip seal by 0.01 inch. This sizing correction made the seal's outer diameter slightly too large, resulting in too much contact with the sealing surface. The increased contact area between the seal and sealing surface created a high level of friction, making the bearing difficult to rotate while pressurized. The pushing force on the inner race required to rotate the bearing cause the races to separate at an angle, which led to destructive failure of the inner race as shown in **Figure 4**.

Tests 2 and 3 revealed a major disadvantage of the lip seal design. Due to the nature of the design, the lip seal sizing required a high level of precision with a tolerance of less than 0.01 inch. Variations in size larger than this were observed to either cause the outer diameter of the seal to be too large to fit inside the sealing surface, or too small to make contact with the sealing surface. This precision and small tolerance is difficult to achieve, and does not allow for slight variation in sizing due to environmental factors, such as humidity, in 3D printing. This, along with the design disadvantages described previously in Section III-B, led to the conclusion that a 3D printed lip seal would not be suitable for use in the PHASE bearings. The problems mentioned above may have been able to be mitigated by using a commercially manufactured lip seal, but was not tested in favor of alternative additive manufacturing solutions.

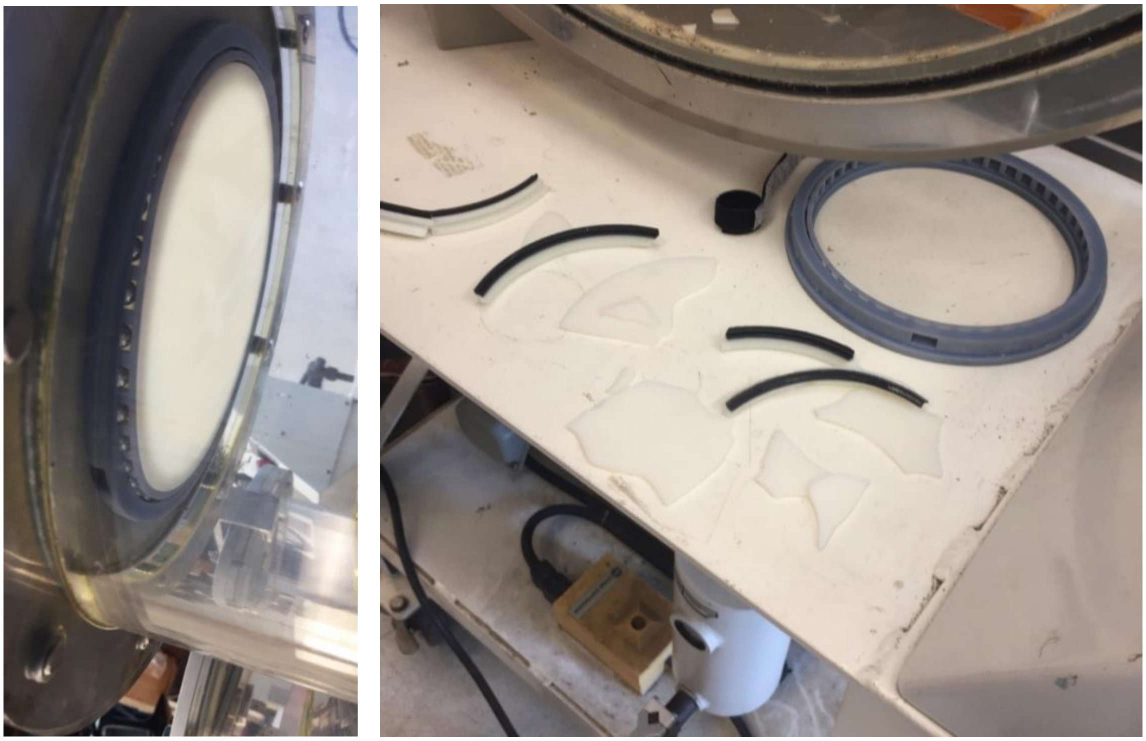


Figure 4. Bearing race began to separate at an angle (left) causing bending forces to act on the inner race. This caused the inner race to fail by breaking in the glovebox (right).

C. Design Iteration Two: X-Ring Seal

Design Iteration Two used an X-ring seal (**Figure 5a** and **Figure 5b**), which mitigated several of the design problems associated with the lip seal. Unlike the lip seal design, this seal did not need to be permanently attached to either of the bearing races. This offered the advantage of independent replacement and easy interchangeability of seals. As shown previously, pressure energized lip seals come to a fine point, making them delicate and therefore difficult to fabricate using 3D printing. The X-ring seal has a more robust design, which helped mitigate these problems.

The X-ring seal also required significantly less sizing precision than the lip seal. It only needed to be slightly larger in diameter than the groove it fit into so that it would be under compression. The results Trial 4 of glovebox tests using Design Iteration Two indicate that it is capable of withstanding a pressure differential of at least 4.0 psi while rotating easily under pressure loads. The results of these tests are displayed in **Table 1b**. Based on these results we selected Design Iteration Two for further testing.

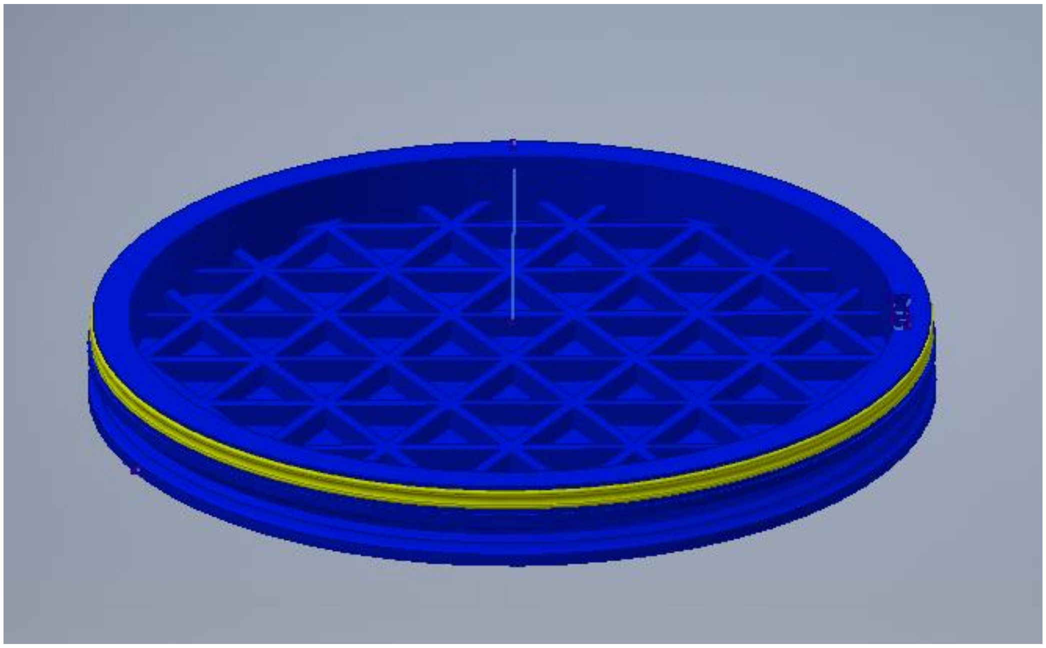


Figure 5a. CAD of X-Ring seal (yellow) integrated onto a modified solid inner race (blue) used for glovebox testing

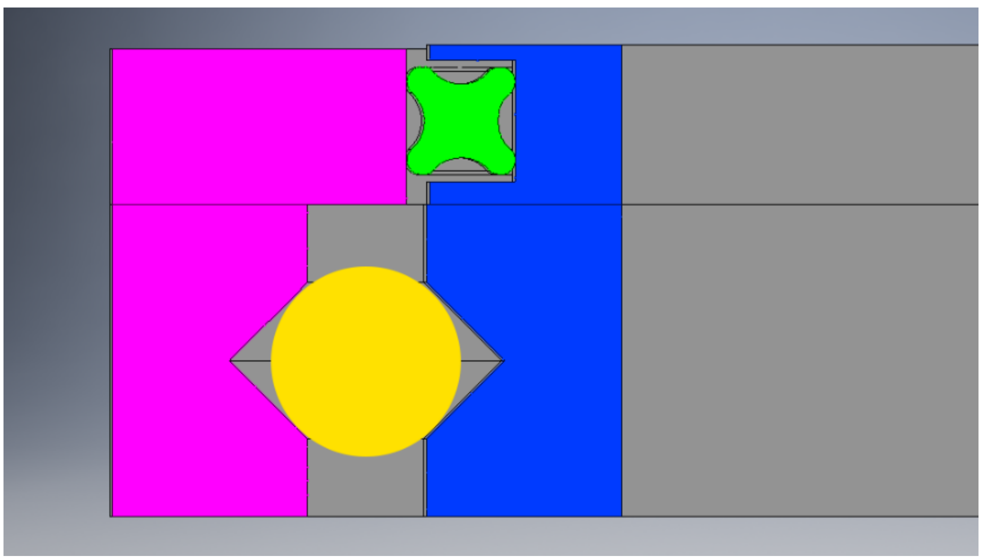


Figure 5b. CAD cross section of the X-ring seal (green) integrated into the PHASE bearings. The outer race in is in blue, the inner race is in pink, and a ball is in yellow.

Table 1b. Glovebox Test Results using Design Iteration Two

Test Number	Seal Material/Manufacturing Process and Hardness	Bearing Race Material/Manufacturing Process	Seal Design	Maximum Pressure Differential (psi)	Notes
4	Commercial, Viton Rubber, Shore 70A	Stratasys' Standard Polyjet Material RGD840 Veroblue	X-Ring	~4.0	-Successful test -Able to rotate easily -Lubricated seal with high pressure grease -smoothed sealing surface with sandpaper
5	Stratasys Flexible Digital Material, Shore 70A	Stratasys' Standard Polyjet Material RGD840 Veroblue	X-Ring	~4.0	-Successful test -Able to rotate easily -Lubricated seal with high pressure grease -smoothed sealing surface with sandpaper
6-12	Commercial, Viton Rubber, Shore 70A	Stratasys' Standard Polyjet Material RGD840 Veroblue	X-Ring	~4.0*	-DuraForm PA (SLS) surfaces are rough -High

*Leaks Observed

Trial 4 was the 1st test of the X-Ring seal design. As noted in Table 1b, the bearing races were fabricated of Stratasys' Veroblue material using a Polyjet printing process, and the seal was commercial Viton. In order to attempt to reduce the friction of rotation, the sealing surface on the Veroblue bearing races was smoothed with fine grit sandpaper and the Viton seal was lubricated to reduce friction. The seal withstood the target pressure differential of 4.0 psi and rotated with minimal friction. This test was notable because it was the first successful test of a hybrid 3D printed seal, and determined that the X-ring seal design was suitable for further testing.

Trial 5 was the 1st test of a fully 3D printed sealed bearing using the X-ring seal design. As in Trial 1 the seal was lubricated and the Veroblue sealing surface was sanded. All other conditions were also kept constant except that the seal was fabricated of Stratasys Flexible Material using a Polyjet Process. This test was notable because it was the first successful test of a fully 3D printed spacesuit bearing and seal.

After completing successful tests of both a hybrid and fully 3D printed sealed bearing using Veroblue races, testing proceeded using DuraForm PA races and commercial X-ring seals. These tests revealed major challenges associated with fabricating sealed bearings from SLS materials. SLS materials have a rough surface finish, which is not ideal for sealing surfaces. This rough surface introduced unacceptably high levels of friction in rotation. Unlike with Polyjet materials, sanding of the sealing surface did not noticeably improve the surface finish.

Though sealed bearings with DuraForm PA races successfully withstood the target pressure differential of 4.0 psi for all trials, they leaked noticeably. This prompted a change in the original test plan because it was necessary to quantify the severity of the leak in the bearing.

IV. Leak Rate Quantification

Following Trial 6, a new test procedure was designed to quantify the leak rate of the DuraForm PA sealed bearings. Before Trial 7, vacuum grease was applied on all surfaces where the bearing races interfaced with the glovebox to minimize potential leaks around the bearing edges. As in previous trials, the test bearings were fitted into a circular opening in the glovebox, and the glovebox was pumped down to a maximum pressure differential of 4.0 psi. The measured maximum pressure differential at this point was actually 3.87 psi, which was used to calculate leak rate. After reaching this maximum pressure differential, the glovebox pump was turned off and time required for glovebox to completely depressurize to atmospheric pressure was measured. The results of these tests are shown in **Table 2**.

Table 2. Leak Quantification Test Results (Glovebox Tests Trials 7-12)

Trial Number	Spinning or Static Bearing Races During Depressurization?	Time for the Glovebox to Fully Depressurize from 3.87 psid (seconds)
7	Static	45
8	Spinning	35
9	Static	40
10	Static	43
11	Spinning	36
12	Spinning	34

The results of these trials were used to calculate mass leak rate. This leak rate was calculated as follows:

(1) The volume of the SSL glovebox was calculated the equation below. The main section of the glovebox is a cylinder. Its two rounded end caps were also approximated as cylinders for this calculation. The volume of the glovebox was found to be approximately 33,200 in^3 or 0.544 m^3

$$V=\frac{\pi D^2}{4}L_{main\ section}+2\left(\frac{\pi D^2}{4}L_{end\ caps}\right)$$

where $L_{main\ section}$= 49.75”, $L_{end\ caps}$= 7”, and D= 25.75”

(2) The number of moles of air in the glovebox at atmospheric pressure (101,320 Pa) and 3.87 psid (74,700 Pa) were then calculated using the ideal gas law. Room temperature (approximately 293 K) was used for calculations.

$$n=\frac{PV}{RT}$$

where P= pressure [Pa], R= universal gas constant [J/K/mol], V= volume [m^3], and T= temperature [K]

$n_{atmospheric}$=22.6 moles and $n_{3.87psid}$= 16.67 moles

(3) The change in moles, denoted Δn, was then calculated. Using this change in moles, change in mass was calculated using the molecular weight of air, 28.0134 g/mol or 0.06176 lb/mol. Mass leak rate was then calculated by dividing this leak rate by the average time required for the glovebox to depressurize.

$$\Delta n = n_{atmospheric} - n_{3.87psid} = 5.95\ mols$$

$$\Delta mass = MW_{air} * \Delta n = 0.3675 \text{ lb}$$

$$Mass\ Leak\ Rate = \frac{\Delta mass}{t_{average}} = 0.009464 \frac{lb}{sec} = 34.07 \frac{lb}{hr}$$

This leak rate is more than 1000 times the acceptable published mass rate for the Apollo Era EMU, 0.0315 lb/hr[5]. While it was not actually necessary to perform these calculations to verify that the DuraForm PA sealing surface was unacceptable, it was beneficial to develop the procedure for future testing of design approaches which come closer to flight requirements.

V. Pressure and Friction Testing

A. Test Design

After selecting a seal design capable of withstanding a pressure differential of 4.0 psi, the sealed bearing was assessed for the ability to withstand the PHASE target operating pressure of 8.3 psi with a safety factor of 3.0 (24.9 psi). The sealed bearing was integrated into a pressure vessel with 4 inch diameter semi-spherical end caps shown in **Figure 6.**

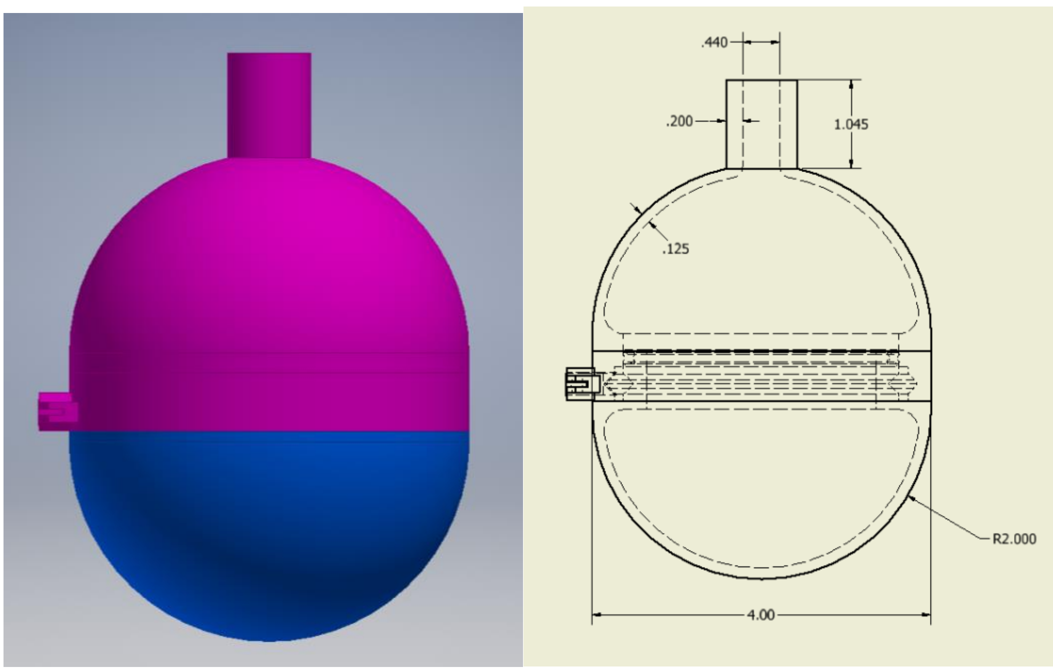


Figure 6. "Spherical" pressure vessel with sealed bearing

At 24.9 psi the sealed bearing "spherical" pressure vessel will experience a hoop stress of 398 psi (2.75 MPa) and an axial stress of 199 psi (1.37 MPa). These stresses were calculated using equations 1 and 2, approximating the pressure vessel to be cylindrical. These stresses are well below DuraForm PA's yield tensile strength of 43 MPa[3A], and Windform XT's tensile yield strength of 83 MPa[6]. Based on these calculations, we expected that the pressure vessels would not burst due to material failure.

$$\sigma_{hoop} = \frac{Pr}{t} \tag{1}$$

$$\sigma_{axial} = \frac{Pr}{2t} \tag{2}$$

The pressure vessel will be submerged in the neutral buoyancy tank in the Space Systems Laboratory and first hydrostatically pressurized to 12.9 psi (4.3 psi with a safety factor of 3.0). The vessel will then be depressurized to atmospheric pressure and inspected. The bearing races will be inspected for pitting, and the seals will be inspected for signs of degradation or damage. After deeming the condition of the bearings and races acceptable, the vessel will then be submerged again and pressurized to 24.9 psi (8.3 psi with a safety factor of 3.0). The vessel will then again be depressurized and inspected for damage.

Following these tests, the vessel will be pressurized to the operating pressure of 8.3 psi. The bearings will be rotated by pulling a line attached to the top hemisphere of the pressure vessel parallel to the bearing races, while the bottom hemisphere is held fixed. A strain gauge measures the force required to rotate the bearings while at operating pressure. Using this force, we can calculate the friction of the sealed bearing.

Pressure and friction testing of sealed bearings is currently underway. We plan on conducting these tests using both commercial X-ring seals and seals 3D printed with Stratasys Polyjet flexible material.

B. Finite Element Analysis

These pressure and friction tests have not yet been conducted due to difficulties in fabricating functional sealed bearings in DuraForm PA. Because of this, a preliminary Finite Element Analysis (FEA) was conducted in Autodesk Inventor to predict the ability of the spherical vessel components to meet a safety factor of 3.0 under the pressure loads prescribed by the test. This analysis was conducted on structural frameworks made of Duraform PA and Windform XT to prove out the basic functionality of the spacesuit structural elements, bearings, and seals under load. The FEA simulates the conditions of the spherical pressure vessel when submerged under neutral buoyancy and subjected to various differentials of 12.9 and 24.9 psi.

The spherical test vessel, shown in **Figure 7**, was fixed at the base and subjected to a uniform pressure load acting on the internal faces of the vessel. Duraform GF, Duraform PA, and Windform XT spherical vessels are simulated; commercial rubber seals and steel bearing balls are present in all analyses. Material properties are assigned to each structural component based on available published data.

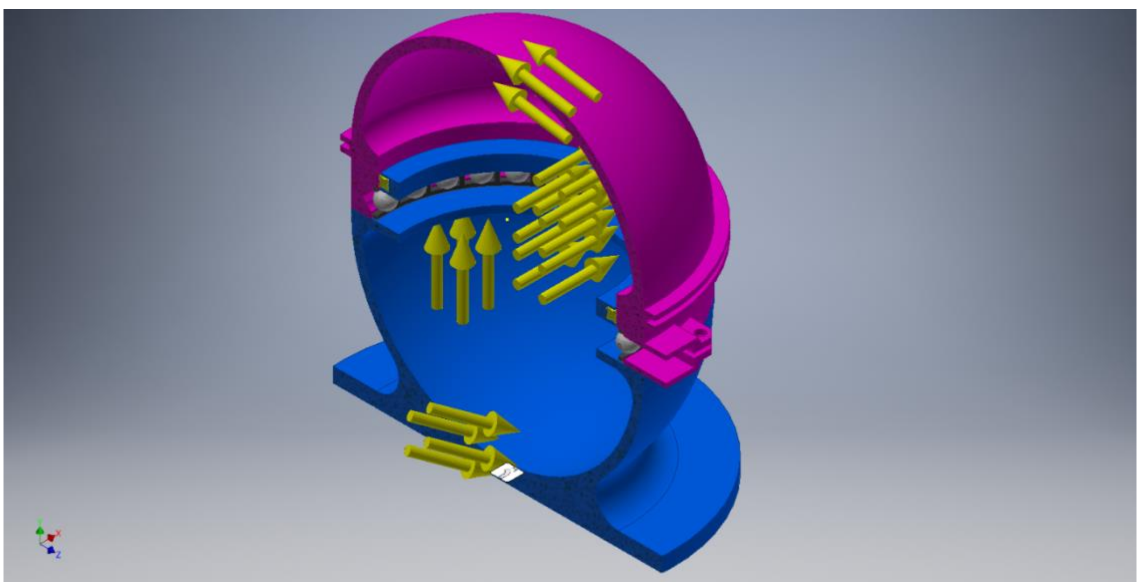


Figure 7. Pressure Loads Applied in Finite Element Analysis

The results of the FEA showed that the test vessel should be able to withstand pressure differential of 4.3 psi with a safety factor of 3.0 in DuraForm PA and a pressure differential of 8.3 psi in WindForm XT. As expected, the results also showed that the maximum stresses occur at the points between the steel balls and the groove of the bearing, which is representative of the common "pitting" effect observed in earlier glovebox bearing tests. Attempts have been made to design against this failure mode in bearings by switching from a four-point angular contact bearing to one featuring a circular groove to increase the surface area over which the structure distributes its loads. However, physical testing of this vessel is required to determine the extent of pitting in the bearing races, as this is likely to be the mode of failure.

VI. Future Work

A. Additional Pressure Testing

Preliminary testing of our sealed rotary bearing design in the Space Systems Laboratory glovebox demonstrated that 3D printed seals were capable of retaining pressure with acceptable joint torques. These tests highlighted significant design challenges brought on by 3D printing, and allowed us to select a potential design for our final PHASE prototype. However, results of these tests demonstrated that only X-ring seals coupled with PolyJet Veroblue bearing races that were able to meet the minimum performance standards set for both pressure retention and friction of rotation. As previously discussed in Section, this material was disqualified as a suitable final prototyping material due to its unpredictable behavior under tensile loads, and because it degrades when exposed to UV light.

Sealed bearings with races fabricated from DuraForm PA withstood the target pressure differential of 4.0 psi without failure, but did not meet minimum performance standards for pressure retention due to significant leaking. The leak rates observed in leak qualification testing are not within acceptable levels. The bearings also failed qualitative friction assessment. The rough sealing surface created by SLS printing processes introduce an unacceptably high friction, making rotation extremely difficult.

One potential solution to mitigate issues caused by the rough sealing surface is to replace it with a smooth metal ring as shown in **Figure 8**. This design modification may drastically improve leak rate and friction of rotation. Another solution would be to attempt to smooth the rough SLS sealing surface with epoxy in post processing. Both of these solutions will require additional testing in the SSL glovebox.

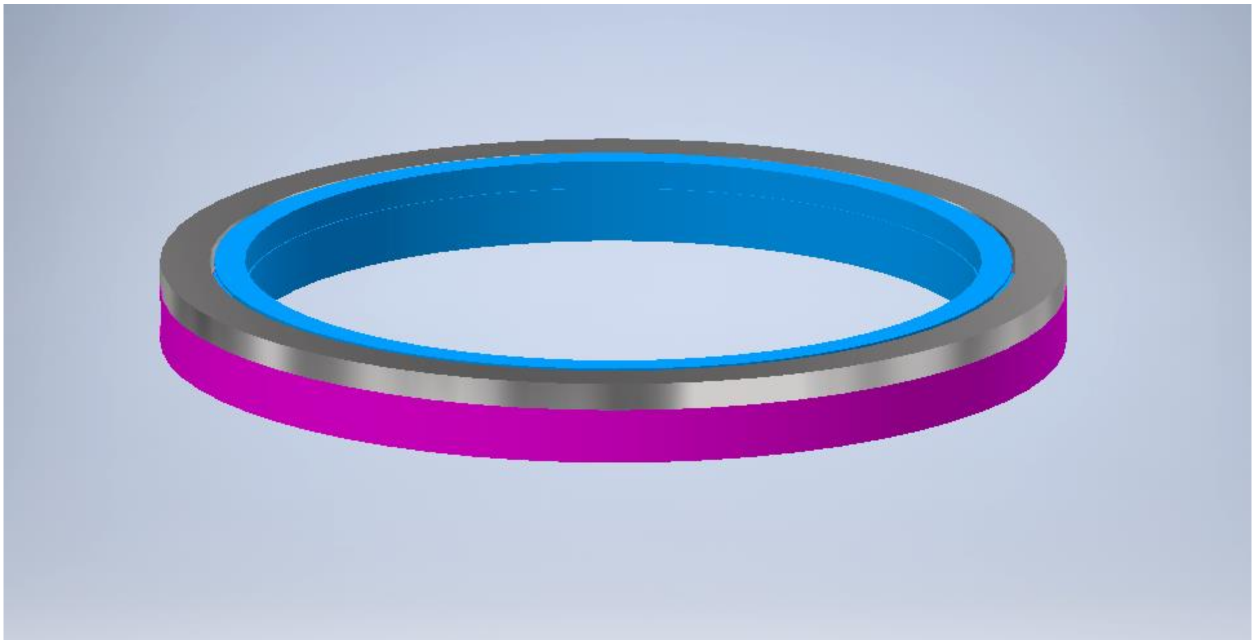


Figure 8. CAD rendering of bearing design with Aluminum sealing surface (silver). This sealing surface will be attached to the outer bearing race (pink/purple)

After completing preliminary testing of a sealed bearing in the SSL glovebox, the design can be integrated into the spherical pressure vessel and undergo the testing procedure described in Section V. The FEA yielded results that indicate that our current bearing design will be able to withstand pressure loads with a safety factor of 3.0. However, FEA cannot adequately assess the torque required to rotate the sealed bearings under pressure. It also is not sufficient to confirm that a prototype using our current bearing design will be safe for human testing. Physical tests are required to determine the effect of pitting in the bearing races and the actual pressure at which the bearings will fail.

B. Lifetime Testing

Lifetime is another critical performance standard for sealed bearings that will need to be quantified in the future. A procedure for evaluating bearing and seals has already been created, and the construction of a test rig is underway. Seal and bearing lifetimes will be evaluated and compared to published data for state-of-the-art Kaydon bearings. The test rig used to evaluate life is shown in **Figure 9**.

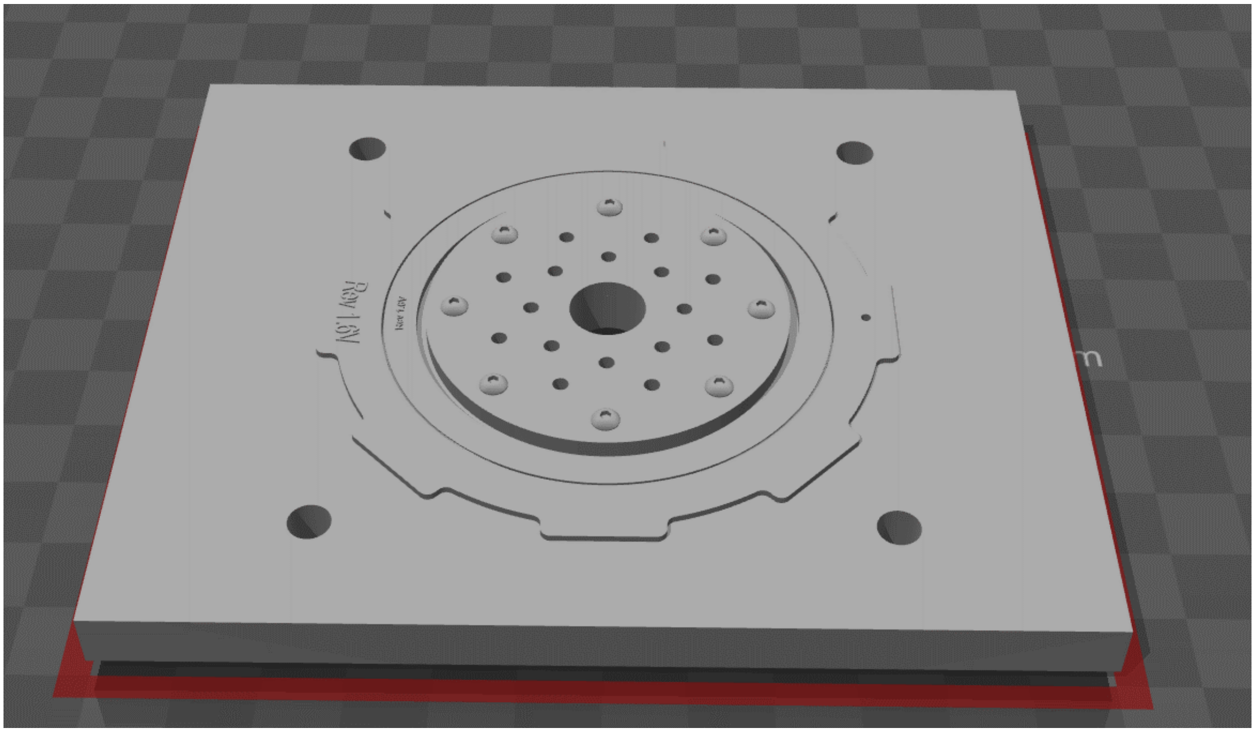


Figure 9. Test rig to evaluate lifetime of bearings and seals

As shown, the top of the test rig will be attached to an elevated table. A motor shaft will be friction fit into the hole in the center of the test bearing from below. The motor repeatedly will rotate the inner bearing race between 0 and 120 degrees, while the outer bearing race remains fixed in place. A potentiometer attached to the motor shaft is used to measure the turn angle of the bearings and to provide feedback to a controlling Arduino, which counts the number of cycles.

After determining the lifetime of the unsealed bearings, the lifetime of the sealed bearings will be determined. Every 10,000 cycles, seals from the sealed bearings used in lifetime testing will be evaluated for the ability to retain pressure in the SSL glovebox following the testing procedure described in Section IIIA. This process will be repeated until seal failure, or until the sealed bearing lifetime exceeds the lifetime of the unsealed bearings.

C. Other Future Work

The tests described in this paper aim to qualify sealed bearings for motion, lifetime, and pressure retention. These functions are essential spacesuit functions that must be met with satisfactory performance before full scale human testing of a prototype in the SSL glovebox. Other factors are also important in qualifying a prototype for use in space. Future work will include outgassing tests of 3D printed materials, exposure of 3D printed materials to radiation, and flammability tests for 3D printed materials, and resistance to micrometeoroid impact. These factors, while critical for complete spacesuit qualification, are not our current research focus. Current focus remains on creating a functional suit that mirrors the kinematics of the AX-5 and performs comparably to the EMU. Other areas of research have the potential to be revisited in the future.

VII. Conclusion

Prior work[1] and theoretical analysis has determined that our final prototype will likely experience bearing or seal failure significantly before material yielding occurs. Because of this, sealed bearing qualification is crucial for the development of a fully 3D printed rigid spacesuit. When completed, the results of testing on such bearings will demonstrate the feasibility of their production for additively manufactured spacesuits. Further testing of the selected design will be conducted to determine its lifetime, ability to withstand our target operating pressure of 8.3 psi, and ability to rotate with minimal friction. If testing yields acceptable results, the design will be integrated into the PHASE prototype, which will be used for human trials in the SSL glovebox.

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