Abrasion Testing of Candidate Outer Layer Fabrics for Lunar EVA Space Suits

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During the Apollo program, the space suit outer layer fabrics were badly abraded after just a few Extravehicular Activities (EVAs). For example, the Apollo 12 commander reported abrasive wear on the boots, which penetrated the outer layer fabric into the thermal protection layers after less than eight hours of surface operations. Current plans for the Constellation Space Suit Element require the space suits to support hundreds of hours of EVA on the Lunar surface, creating a challenge for space suit designers to utilize materials advances made over the last forty years and improve upon the space suit fabrics used in the Apollo program. A test methodology has been developed by the NASA Johnson Space Center Crew and Thermal Systems Division for establishing comparative abrasion wear characteristics between various candidate space suit outer layer fabrics. The abrasion test method incorporates a large rotary drum tumbler with rocks and loose lunar simulant material to induce abrasion in fabric test cylinder elements, representative of what might occur during long term planetary surface EVAs. Preliminary materials screening activities were conducted to determine the degree of wear on representative space suit outer layer materials and the corresponding dust permeation encountered between subsequent sub-layers of thermal protective materials when exposed to a simulated worst case eight hour EVA. The test method was used to provide a preliminary evaluation of four candidate outer layer fabrics for future planetary surface space suit applications. This paper provides a review of previous abrasion studies on space suit fabrics, details the methodologies used for abrasion testing in this particular study, and shares the results and conclusions of the testing.

I. Introduction

One of the challenges in designing the next generation of space suits is to provide astronauts with durable space suits which will survive many hours of Extravehicular Activity (EVA) on a planetary surface. During the Apollo program, space suits came back to earth both abraded and penetrated by lunar dust after just two to three EVAs. Future NASA planetary design reference missions call for upwards of one hundred EVAs over multi-month missions, setting space suit engineers up with a major design challenge.

In an effort to prepare for this challenge, abrasion testing was performed at the NASA Johnson Space Center in 2009 to provide a preliminary evaluation of existing candidate outer layer fabrics for planetary EVA space suits. Testing exposed four candidate materials to lunar simulant in a simulated eight hour worst case EVA. The testing evaluated the abrasion resistance of the various fabrics to two types of lunar simulants, as well as evaluated the ability of heat sealed seams to prevent dust migration through space suit components. Data was collected via visual inspections, pre- and post-test material strength measurements, and pre- and post-test optical and scanning electron microscopy. This paper introduces the reader to the various abrasion test methodologies which have been used in the past, describes the test method used in this specific study, and provides results and conclusions.

II. Description of Previous Similar Abrasion Test Efforts

Previous abrasion tests have been developed and performed over the past two decades at both the NASA Johnson Space Center (JSC) and NASA Glenn Research Center (GRC). The tumble test methodology was first developed at JSC by Joseph J. Kosmo in 1990 to screen advanced space suit materials. Test activities included the preliminary screening of five candidate outer layer materials using a tumble test method to simulate eight hours of worst case Extravehicular Activity (EVA). After tumbling, the fabrics were inspected visually and through Scanning Electron Microscopy (SEM). In addition to performing SEM on the candidate fabrics, an SEM analysis was also conducted on the outer layer of Alan Bean's Apollo 12 space suit to serve as a baseline of the abrasion experienced on the lunar surface. The report based off of this analysis, written by Mary J. Hennessy[1], was used as a guideline and a comparison tool for the current test effort. The outcome of this initial abrasion study showed that Gore-tex fabric

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with a 2 mil. FEP (Teflon) laminated back face out-performed the other four fabrics against abrasion. The other fabrics investigated were standard Orthofabric, Orthofabric – back face coated with 10 mil. Silicone, Gore-tex – front face laminated with 2 mil. FEP (Teflon), and Apollo Test Article Teflon (T162).

A second round of tumble testing was performed in 1997, which looked at two back-face laminated Gore-tex fabrics, one plain weave and one twill weave, both with and without heat sealed seams. This second study did not include SEM analysis, but rather, focused on the amount of dust absorbed in each of the four test cases, as well as the amount of dust penetration through the outer layer fabric. The results of this study showed that the plain weave fabric absorbed less dust on average, regardless of whether or not the seams were heat sealed; however, all cylinders were very close in collected dust weight, making it hard to draw concrete conclusions from just four total test cylinders. Visual inspection of the cylinders showed that the twill weave cylinders received more significant abrasive wear than the plain weave cylinders. In all trials, the end-caps showed more wear than any other part of the cylinders. The test report[2], prepared by Joseph J. Kosmo and Michael Castillo, recommended a second round of testing to examine the consistency of data collection techniques, as well as to make minor modifications to the cylinders. It is not known if this additional testing was ever carried out.

In addition to the tumble test abrasion method, GRC developed a second method of evaluating fabrics for abrasion resistance to lunar regolith in 2008 under the EVA Technology Development Program (ETDP) Dust Management Project (DMP). The objective of the GRC effort was to develop a standardized set of procedures by which to compare the relative abrasion resistance of candidate EVA fabrics. The test team performed optical and SEM analysis on a sample of Alan Bean's Apollo 12 suit, and used the images to evaluate the ability of various test protocols to produce similar abrasive wear. The final protocol was based on an ASTM standard test: ASTM D 3884-01, "*Standard Guide for Abrasion Resistance of Textile Fabrics (Rotary Platform, Double Head Method)*", with modifications to introduce loose lunar simulant onto the test apparatus. During development of the test protocol, GRC also evaluated several candidate EVA fabrics, including Apollo plain weave FEP, Apollo twill weave FEP, Orthofabric, Tyvek, silicone coated Orthofabric, silicone coated Kevlar, and silicone coated Vectran material. The final test protocol was only run on the latter four fabrics: Kevlar, silicone coated Orthofabric, silicone coated Kevlar, and silicone coated Vectran. Results of the testing were documented in a test report[3], as well as published in a 2009 ICES paper[4]. Out of the four fabrics tested using the final protocol, Tyvek reportedly performed the best, sustaining the least abrasive damage and blocking dust from penetrating the fabric.

III. Test Hardware

A. Rotary Drum Tumbler

The tumble testing was carried out in 16 inch diameter by 20 inch long rotary drum tumbler, Fig. 1, which was built in-house at the Johnson Space Center (JSC) for previous tumble test activities. The tumbler was belt driven by a one-quarter horsepower motor at a rate of 13 rotations per minute. A cycle counter was added to the tumbler for this test series to accurately track the cylinder cycle count through the test. Additionally, a timer was used to ensure automatic shut-off after the desired test length.

B. Simulated Planetary Surface Materials

Figure 1. Rotary Drum Tumbler. *Drum tumbler was used to simulate 8-hour EVA with each test article.*

Simulated planetary surface materials were used as abradant in the tumble test. Two different lunar simulants were used in the test, JSC-1 – representing lunar mare regions, and NU-LHT-2C – representing lunar highland regions. For each test run, 10 ounces of lunar simulant and 3 pounds of various sized lunar simulant rocks were inserted into the rotary drum tumbler. The lunar simulant rocks replaced volcanic rock, which was used in previous tumble tests performed in the rotary drum tumbler. The volcanic rock reportedly wore down after a few hours of tumbling, which likely decreased its ability to produce abrasion on the test articles through the entire duration of the test. The lunar simulant rocks were fabricated in the Crew and Thermal Systems Division (CTSD) Advanced Suit Laboratory from a mixture of lunar simulant and wood glue, and were determined through preliminary testing to be more abrasive than volcanic rock over an eight hour period.

C. Fabric Test Cylinders

The fabric test cylinders were designed to be representative of a typical space suit upper leg assembly, and were composed of two separate elements: a bladder/restraint assembly and a cover layer. The bladder/restraint assembly was an 8 inch diameter by 15 inch length element representative of the space suit bladder and restraint layers. This element was originally planned to be composed of standard space suit urethane coated nylon bladder cloth, supported by polyester (Dacron) restraint fabric, and pressurized to 4.3 psi. However, the fabricated bladder was too light-weight to provide an accurate representation of an upper leg element. Therefore, a foam core was used as the bladder layer to achieve a more realistic representative weight. The foam was covered by a Dacron restraint layer. The same bladder/restraint assembly was used for all test articles.

Figure 2. Cover layer lay-up. *Lay-up used for all cylinder cover layers. From inside to outside: one layer neoprene coated nylon rip-stop, five layers aluminized Mylar, one layer candidate fabric.*

The cylinder cover layer was an 8 inch diameter by 15 inch length cylindrical element representative of the space suit thermal micrometeoroid-dust garment (TMDG). The cover layer was constructed with standard space suit fabrication techniques and was designed to fit over the bladder/restraint assembly, as the thermal micrometeoroid garment (TMG) fits over the Extravehicular Mobility Unit (EMU) space suit assembly. The cover layer was left open at one end, to allow for insertion of the bladder/restraint element. A fabric end-cap attached to the element through a Velcro enclosure. The cover layer for all test articles was comprised of the following materials (from innermost to outermost layer):

1) One (1) layer of standard Shuttle EMU neoprene coated nylon rip-stop
2) Five (5) layers of standard Shuttle EMU aluminized Mylar
3) One (1) layer of candidate outer fabric material

The only variation between test articles was the outermost (i.e. candidate outer fabric material) layer. For this test, four (4) candidate fabrics were evaluated through a total of nine (9) test cases. The four candidate fabrics evaluated in this tumble test were as follows:

1) Standard Shuttle EMU Orthofabric
2) W.L. Gore #R8127 4 Harness Satin with back face coated with Teflon
3) W.L. Gore #V112671 3x1 Right-hand Twill with back face coated with Teflon
4) Tyvek® 1443R Soft Structure non-woven fabric

In an attempt to build on previous work in the arena of abrasion resistance of space suit fabrics, past abrasion test reports were used to help select the candidate materials for this study. Orthofabric was chosen as a baseline fabric due to its use as the outer layer of the current NASA EVA space suit. Both plain and twill weave Teflon coated W.L. Gore fabrics were chosen due to success with them in previous tumble testing. Tyvek was chosen as the fourth and final material, based on results of the 2008 Glenn Research Center study[3].

IV. Test Objectives and Methodology

Figure 3. Example fabric test cylinder. *Fabric test cylinder before tumble test.*

A. Objectives

The primary objective of the Abrasion Testing of Candidate Outer-Layer Fabrics for EVA Space Suits was to build on past work and provide a preliminary evaluation of various candidate outer layer fabrics for planetary surface space suit applications. Secondary objectives of the testing included comparing abrasive wear produced by two different lunar simulant types and evaluating the ability of heat sealed seams to prevent dust migration through space suit components.

B. Test Protocol

Test Article	Candidate Outer Layer Fabric	Simulant Type	Heat Sealed Seams?
1	Fabric 1: Orthofabric	JSC-1	No
2	Fabric 2: Gore-tex Satin	JSC-1	No
3	Fabric 3:Gore-tex Twill	JSC-1	No
4	Fabric 4: Tyvek	JSC-1	No
5	Fabric 2: Gore-tex Satin	JSC-1	Yes
6	Fabric 3: Gore-tex Twill	JSC-1	Yes
7	Fabric 1: Orthofabric	NU-LHT-2C	No
8	Fabric 2: Gore-tex Satin	NU-LHT-2C	No
9	Fabric 3: Gore-tex Twill	NU-LHT-2C	No

Table 1. Tumble test matrix. *The above table describes the test conditions for the nine test articles used throughout the course of testing.*

The tumble test was divided into various phases. Prior to the start of testing, pre-test visual inspection and photo documentation was performed to document the initial condition of all test articles. Each test article was then put through an 8-Hour EVA Simulation. During this phase, the test article was placed inside the rotary drum tumbler, along with 3 pounds of lunar simulant rocks and 10 ounces of lunar soil simulant. The rotary drum tumbler was then closed and sealed, and turned on to run for 8 hours. At the conclusion of the 8 hour period, the tumbler stopped automatically. The test conductor then recorded the number of cycles and removed the test cylinder from the rotary drum tumbler. Post-test inspection and photo documentation was performed to document the post-test condition of all test articles. The method used for visual inspection is described in more detail in the Data Collection Techniques section of this paper. Once the visual inspection was complete, post-test cleaning and dust collection was performed. Post-test cleaning and dust collection consisted of removing residual dust adhering to the cylinder by hand and with a dust removal brush, followed by using a standard Shop-Vac vacuum cleaner to remove additional dust. During this phase, any dust which had migrated through the cylinder outer-layer was collected and weighed, to provide a quantitative measurement of dust permeation for the various test articles.

As mentioned in the Test Hardware section of this paper, the tumble test evaluated four (4) candidate fabrics through a total of nine (9) test cases. The test matrix in Table 1 describes the test cases evaluated.

As noted in Table 1, the four candidate fabrics were first evaluated in an initial condition, which used JSC-1 simulant, with normal seam construction (Test Articles 1-4). These conditions replicated the test protocol used on past tumble tests. In past tumble tests, seam sealing techniques were also evaluated and had proven to cut down on dust migration. Therefore, Test Articles 5 and 6 looked at the effects of heat sealing the seams on two of the candidate fabrics. The heat sealing was performed by W.L. Gore. Since the heat sealing process used is a W.L. Gore proprietary process, only the cylinders using W.L. Gore candidate fabrics were heat sealed. Two samples were thought by the test team to be sufficient to evaluate the effects of heat sealed seams.

This series of tumble testing was performed during an ongoing effort at the Marshall Space Flight Center (MSFC) to develop lunar simulants representing various areas of the lunar surface. At the time of this testing, the MSFC had not yet characterized the abrasiveness of the various simulants. Therefore, the final test articles (Test Articles 7-9) looked at the effect of a second type of lunar simulant on the fabrics, to attempt to determine whether JSC-1, a Mare simulant, or NU-LHT-2C, a lunar highlands simulant, caused more abrasive damage to space suit fabrics. Only 3 of the 4 candidate fabrics were tested with the highlands simulant. Tyvek was left out of this portion of the test because it performed very poorly with the first simulant. It was therefore deemed unnecessary to test it with a second stimulant.

C. Data Collection Techniques

Data from the tumble test was collected through the following three techniques, each of which is described in detail in this section:

1) Visual Inspection
2) Pre-/Post-Test Strength of Materials Measurements
3) Optical and Scanning Electron Microscopy

As described in the Test Protocol section of the paper, both pre- and post-test visual inspections were performed on all test articles. The visual inspections consisted of inspecting all layers of the test articles and documenting any observable wear and dust permeation. Additionally, photographs were taken to document the pre- and post-test condition of the test articles. The data collected during visual inspections served as an initial indicator of how well the various fabrics performed.

Pre- and post-test strength of materials measurements were collected for all test articles used in the tumble test. To collect this data, the Crew and Thermal Systems Division (CTSD) Advanced Materials Laboratory performed the following three standard tests used to document material strengths:

1) Tensile Strength Testing
2) Tear Strength Testing
3) Burst Strength Testing

All three tests were performed on pristine samples of the four candidate fabrics, as well as on post-test samples from each of the nine tumble test articles. The strength of materials measurements served as an indicator of material strength degradation as well as a tool to compare the strengths of the various candidate fabrics before and after testing.

Optical Microscopy and Scanning Electron Microscopy (SEM) were performed on the tumble test articles. Microscopy was performed on pristine samples of each of the four candidate fabrics, as well as on post-test samples of several of the tumble test articles. Due to time and budget limitations, microscopy was only performed on the test articles tumbled with JSC-1 simulant. The limited microscopy allowed for meeting the primary test objective, to compare the performance of the four candidate fabrics. All conclusions drawn comparing the two stimulant types, which was a secondary objective, was collected through visual inspections and strength of materials testing alone.

V. Test Results

The test results will be presented in this section according to the three methods of data collection: visual inspection, strength of materials testing, and microscopy.

Figure 4. Test article pre-/post-test photos. *Photographs of Test Article #1, the Orthofabric test cylinder, before (top) and after (bottom) tumbling for 8 hours with JSC-1 simulant.*

A. Visual Inspection

As described in the Data Collection Techniques section of the paper, all cylinders were visually inspected before and after testing. The most noticeable change in all test cylinders, as displayed in Figure 4 to the left, was the color of the fabric. The lunar simulant became embedded in all fabrics, turning the cylinders from white to gray during the course of testing. Figure 4 shows Test Article #1, the Orthofabric test article, before and after being tumbled with JSC-1 simulant. In the after photo, the cylinder has been tapped and brushed to remove residual dust. Even after vacuuming the cylinders, all cylinders still retained a gray hue post-testing (Figure 5).

In addition to the noticeable change in color of the test articles, another common theme seen during the visual inspections was abrasion on the cylinder end-caps, specifically near the edges, as shown in Figure 6. It is believed that the most damage was seen on the end-cap edges due to the sharp corner that was formed on the cylinders in that area. Other than the wear in this location, no other significant damage was visible to the naked eye on any of the Orthofabric or W.L. Gore fabric cylinders. When compared using visual inspection alone, all fabrics except for Tyvek displayed a comparative amount of abrasive wear.

Figure 5. Test article post vaccuming. *Test Article #1, the Orthofabric test cylinder, after being vacuumed to remove simulant.*

Figure 6. Damage on test article end-cap. *One of the common themes across test articles was abrasive wear on the end-caps. The photo above displays wear as seen on the Test Article*

The test article using Tyvek fabric performed far worse than any of the other test cylinders. As shown in Figure 7, the Tyvek demonstrated much more degradation than the Orthofabric. Figure 8 provides a close-up look at the damaged Tyvek cylinder.

The Tyvek fabric is an overall much lighter weight and thinner fabric than the other fabrics used in this test, and the severe damage it displayed is likely a result of these factors. Tyvek is typically used in one-time use garments, such as haz-mat suits, and as the test results showed, is not necessarily designed for use in a durable, multi-use garment such as a space suit thermal micrometeoroid dust garment (TMDG).

Figure 7. Comparison of Orthofabric and Tyvek post-testing. *As shown above, the Tyvek test article displayed much more degradation post-testing than other fabrics, such as the Orthofabric.*

One factor worth noting is that the Tyvek used in this testing, Tyvek 1443R soft structure non-woven fabric) was different from the Tyvek used in the Glenn Research Center (GRC) testing, in which Tyvek reportedly out-performed several other materials in resistance to abrasion. The GRC testing used Tyvek 1073D hard structure non-woven fabric. It was originally planned to use the same Tyvek material in the tumble testing; however, upon receipt of the Tyvek material, it was discovered that the hard structure Tyvek used in the GRC testing is a very paper-like material, and it would not be practical or feasible to use this material to form a garment such as the TMDG outer-layer. Therefore, the Tyvek soft structure, which is commonly used in garments, was chosen as the tumble test material.

Figure 8. Close-up of damaged Tyvek cylinder. *The figure above provides a close-up look at the damaged Tyvek cylinder, including a tear in the fabric.*

In addition to comparing abrasive wear on the various fabrics, as noted in the test objectives, the secondary test objectives included comparing abrasive wear produced by two different lunar simulant types and evaluating the ability of heat sealed seams to prevent dust migration through space suit components. Three of the four fabrics (all except for Tyvek) were tumbled with both the JSC-1 and NU-LHT-2C simulants. Data collected from the visual inspections demonstrated little to no difference in performance of the three fabrics between the two simulant types. Similar wear was seen on the end-caps using both simulants, and no other wear was visible to the naked eye. The only real difference noticed during the visual inspections was that the fabrics turned a lighter gray color when tumbled with the NU-LHT-2C simulant than they did when tumbled with the JSC-1 simulant, as displayed in Figure 9. This difference in hue makes sense, as the NU-LHT-2C simulant itself has a lighter hue than the JSC-1 simulant.

The other secondary test objective, evaluating the ability of heat sealed seams to prevent dust migration through space suit components was accomplished by tumble testing two test articles with heat sealed seams. Test articles #5 and #6 were identical to test articles #2 and #3, other than the

Figure 9. Comparison of hue between simulant types. *The JSC-1 simulant turned test articles a darker shade of gray than the NU-LHT-2C simulant, as shown above. Test articles pictured are Test Article #2 (top) and Test Article #8 (bottom), both fabricated from the W.L. Gore 4 Harness Satin material.*

addition of heat sealed seams. From visual inspection alone, it was hard to determine if the heat sealed seams had any effect on the test results. The goal was to measure the dust that migrated through each of the cylinders, and compare the amount that migrated through the cylinders with normal seam construction to the amount that migrated through the cylinders with heat sealed seams. However, as mentioned previously, all test articles experienced small abrasions/tears on their end-caps. These tears allowed dust to accumulate beneath the outer-layer on all test articles, which made it impossible to determine whether dust inside the outer-layer migrated through the seams of the fabrics or came in through the small holes. During the microscopic analysis, areas of the cylinders near the seams were examined to look for dust migration, and this topic will be described in more detail in the microscopic analysis results section.

B. Strength of Materials Testing

As described in the Data Collection Techniques section of the paper, pre- and post-test strength of materials measurements, including tensile, tear, and burst strength were taken on each of the test articles. The results of the strength of materials testing are presented in this section of the paper.

As described in the test matrix (Table 1), the first six test articles were tumbled with JSC-1 simulant material. The tensile strength graph for these six test articles, both before and after testing, is displayed in Fig. 10. As seen in the Fig. 10, Orthofabric (Test Article #1) began with a tensile strength that was approximately three times that of the next strongest material, which resulted in an end tensile strength which was greater than the pre-test material strength of any of the other three fabrics. It was by far the strongest material tested. From a pure degradation standpoint, the Orthofabric and both Goretex fabrics (Test Articles #2 and #3), had a similar % degradation in tensile strength after testing. Both Gore-tex fabrics were very close in tensile strength both before and after testing. Additionally, the addition of heat sealed seams had no real effect on the post-test tensile strength of the Gore-tex fabrics, which was an expected result. Interestingly, the Tyvek material had the least % degradation in tensile strength; however, it's extremely low tensile strength, as demonstrated by the post-test visual inspection, was unacceptable.

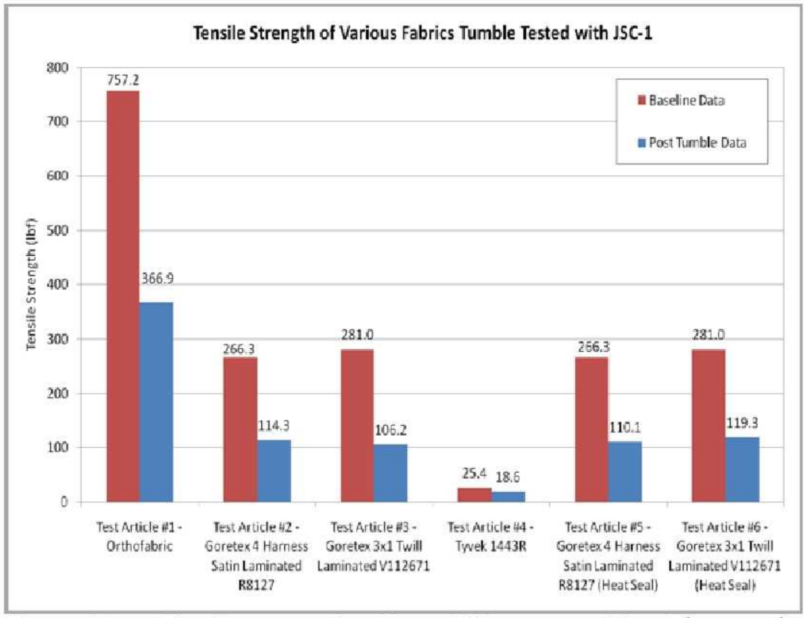


Figure 10. Tensile strength of candidate materials. *The graph above displays the tensile strength of 6 of the 9 test article fabrics before and after testing.*

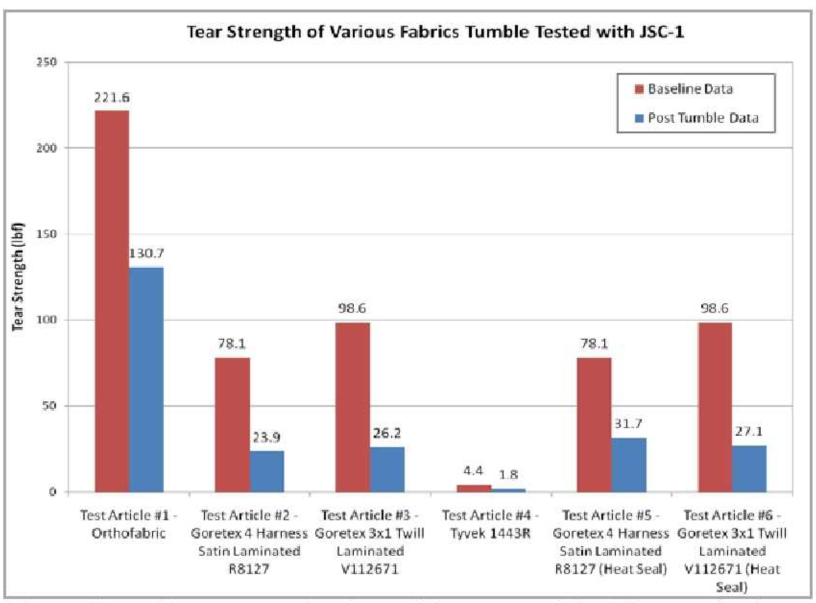


Figure 11. Tear strength of candidate materials. *The graph above displays the tear strength of 6 of the 9 test article fabrics before and after testing.*

The tear strength results (Fig. 11) for Test Articles #1 - #6 were

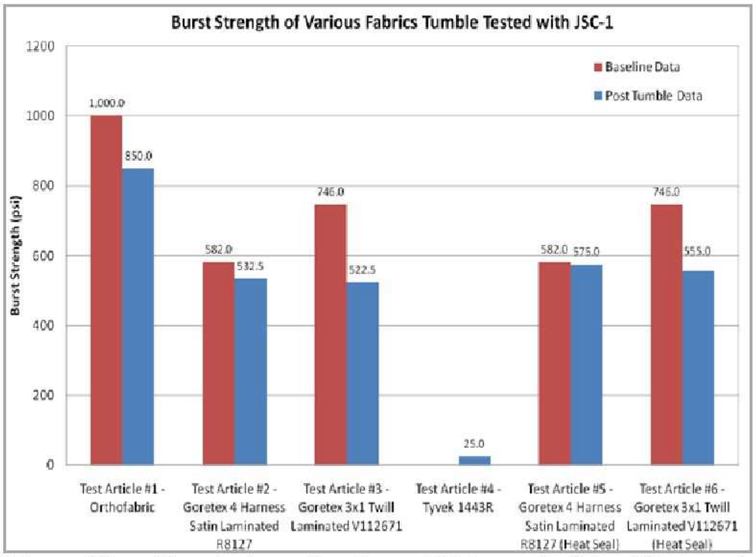


Figure 12. Burst strength of candidate materials. *The graph above displays the burst strength of 6 of the 9 test article fabrics before and after testing.*

very similar to the tensile strength results. Orthofabric was again the strongest material by far, both before and after testing. However, unlike the tensile strength test, Orthofabric had a much smaller percentile degradation after testing than either of the Gore-tex fabrics. The Gore-tex fabrics were again similar in strength. The twill weave Gore-tex had a noticeable higher tear strength prior to testing than the 4 harness satin Gore-tex; however, the two fabrics displayed mixed results post testing. The Tyvek material was again clearly the weakest material, as displayed by both its pre- and post test tear strength (Fig. 11).

In addition to tensile and tear strength measurements, burst strength was also calculated for each of the test articles. The pre- and post- test burst strength measurements for the six of the nine test articles are displayed in Fig. 12. The burst strength measurements followed most of the same trends as the other material strength measurements. Orthofabric was again the strongest material, and Tyvek the weakest. In this test, the Gore-tex twill weave fabric was significantly stronger than the Gore-tex 4 harness satin prior to testing, but both materials had very similar strengths post test.

Strength of materials measurements were also taken for Test Articles #7-9, which were tumbled with the NU-LHT-2C simulant; however, due to inconsistencies in how the testing was performed (i.e. measurements were taken in a different fabric direction), the majority of the results cannot be directly compared back to those from the test articles tumbled with JSC-1, and therefore will not be presented in this paper. In the few cases where testing was consistent between simulant types, the results showed similar degradation of materials, leading the author to believe that the JSC-1 and NU-LHT-2C simulants cause comparable damage when tumbled with various materials. Further testing is required to confirm this belief.

C. Optical and Scanning Electron Microscopy

As described in the Data Collection Techniques section of this paper, the third method of data collection used in this test was optical and scanning electron microscopy (SEM), to take a close up look at the test articles. A sampling of the microscopy results are presented in this section of the paper. More detailed microscopy results are presented in the test report[5].

SEM was performed on the four candidate fabrics in a pristine condition, as well as on test articles #1-4 in post-test dirty and cleaned configurations. As described in Table 1, test articles #1-4 consisted of one cylinder of each of the four candidate fabrics, and did not have heat sealed seams. Additionally, these test articles were all tumbled with JSC-1 lunar simulant. The following series of tables (Tables 2-5) present SEM images of each of the four fabrics in both pristine and post-tumbling conditions at various levels of magnification.

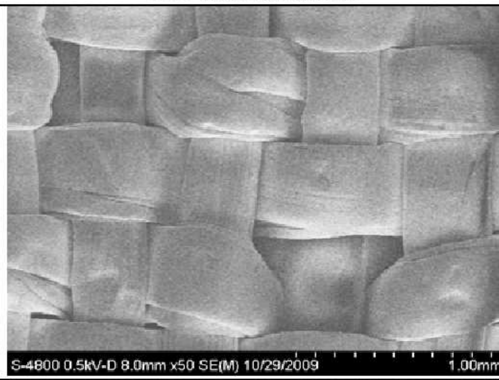
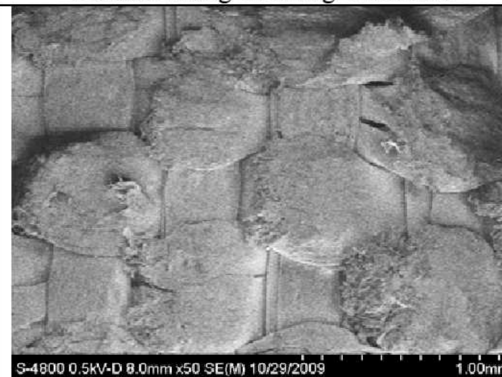
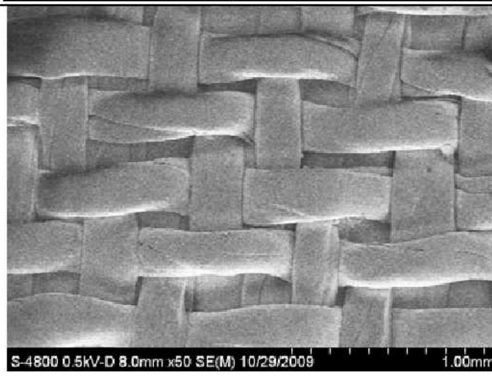
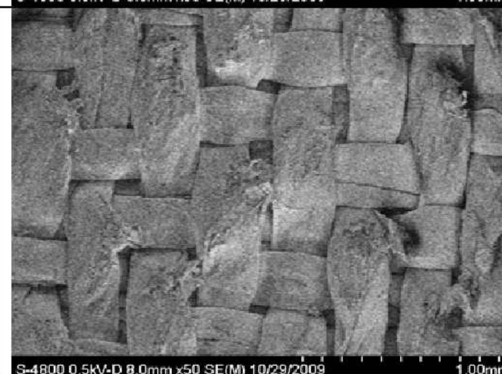
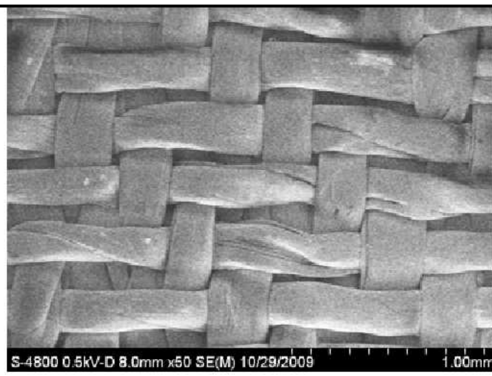
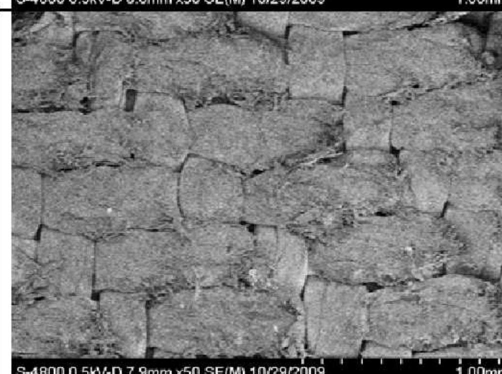
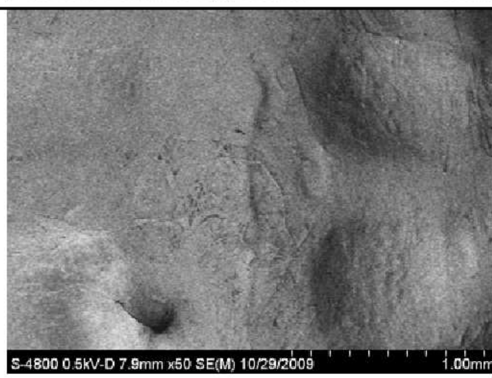
Test Article	Pre-Test Condition	Post Tumbling/Cleaning Condition
#1 - Orthofabric		
#2 – Gore-tex 4 Harness Satin		
#3 – Gore-tex 3x1 Twill		
#4 - Tyvek		

Table 2. Scanning electron microscope images at 50x magnification. *The above table displays SEM images of the four candidate fabrics at 50x magnification before testing and after testing/cleaning.*

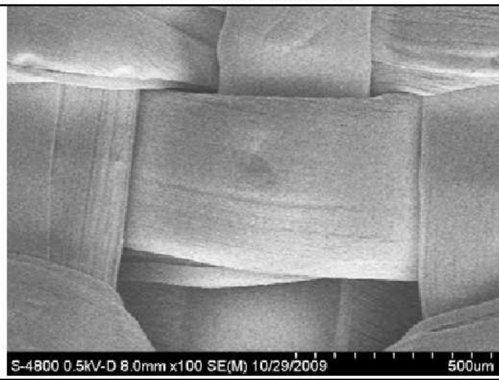
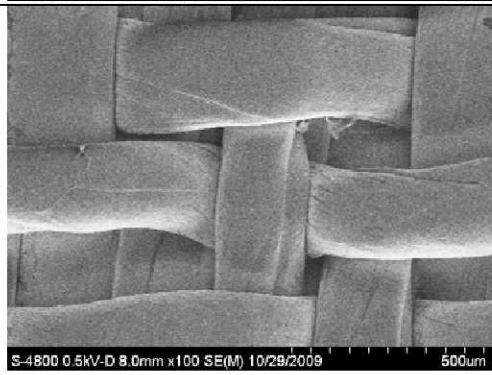
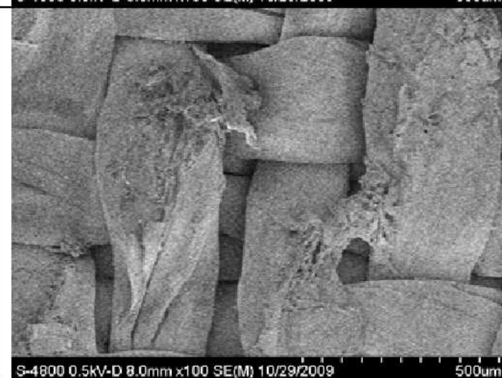
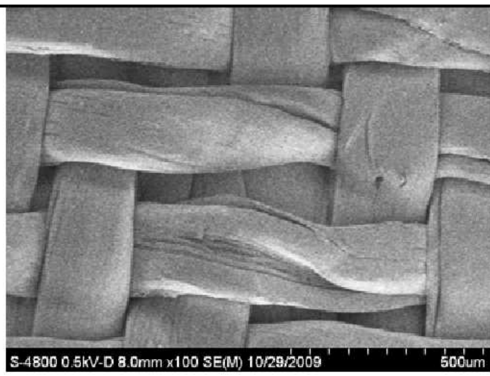
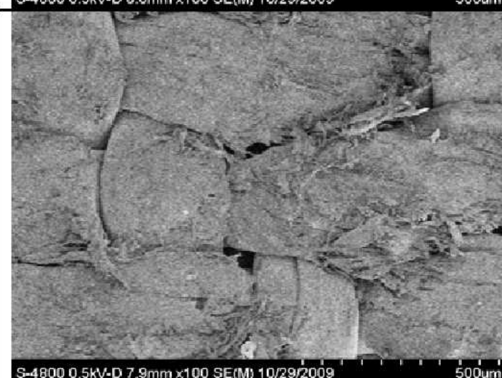
Test Article	Pre-Test Condition	Post Tumbling/Cleaning Condition
#1 - Orthofabric		
#2 – Gore-tex 4 Harness Satin		
#3 – Gore-tex 3x1 Twill		
#4 - Tyvek		

Table 3. Scanning electron microscope images at 100x magnification. *The above table displays SEM images of the four candidate fabrics at 100x magnification before testing and after testing/cleaning.*

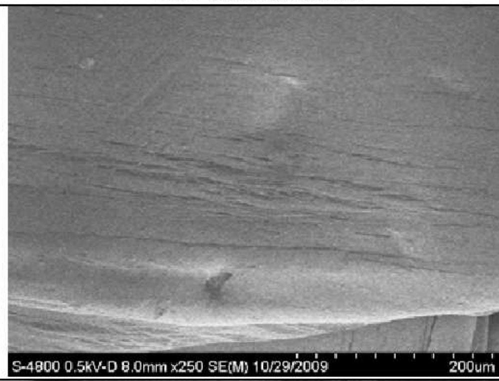
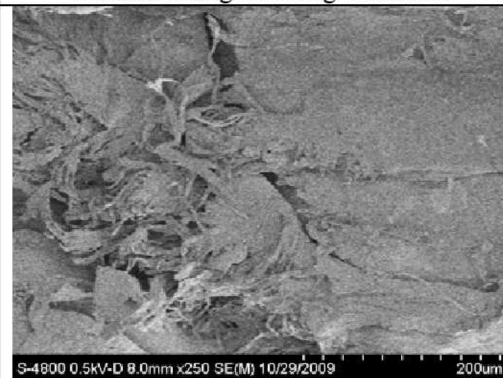
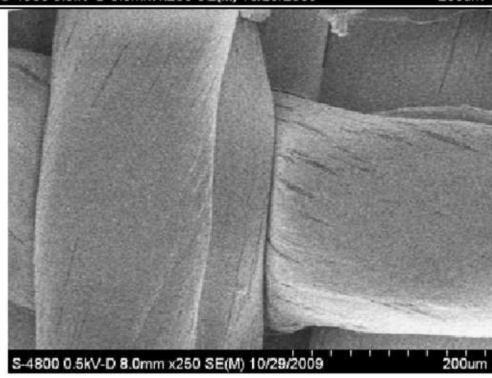
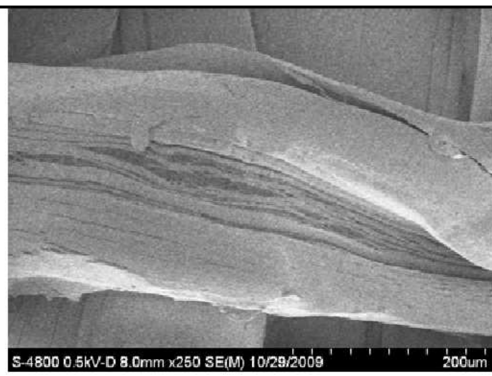
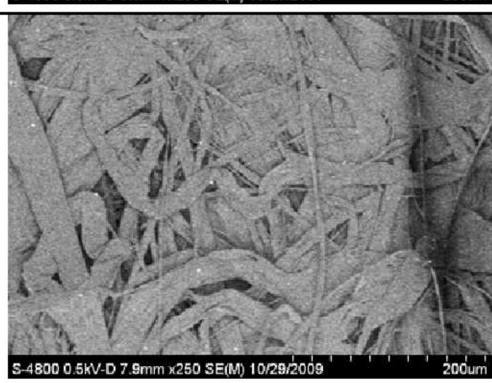
Test Article	Pre-Test Condition	Post Tumbling/Cleaning Condition
#1 - Orthofabric		
#2 – Gore-tex 4 Harness Satin		
#3 – Gore-tex 3x1 Twill		
#4 - Tyvek		

Table 4. Scanning electron microscope images at 250x magnification. *The above table displays SEM images of the four candidate fabrics at 250x magnification before testing and after testing/cleaning.*

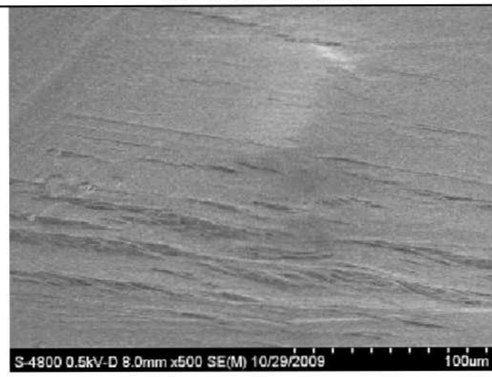
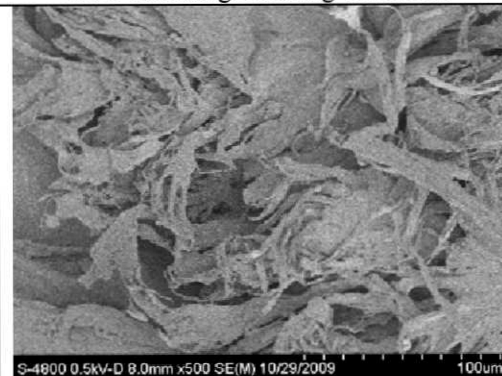
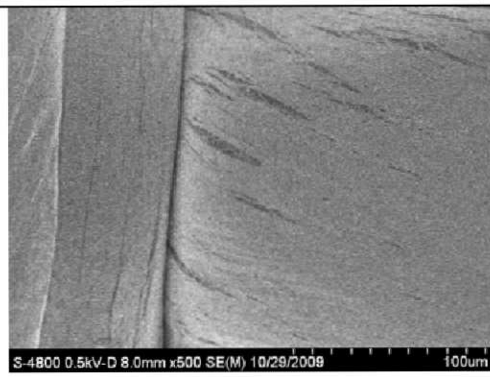
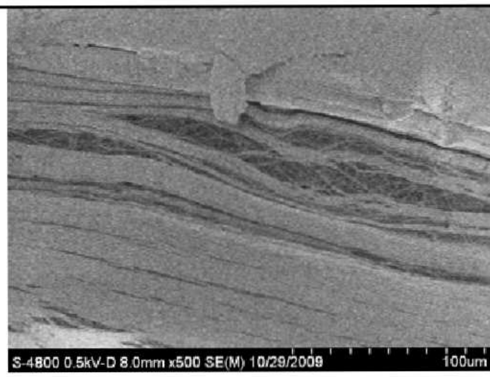
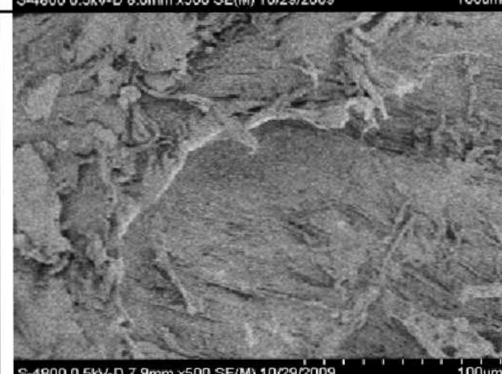
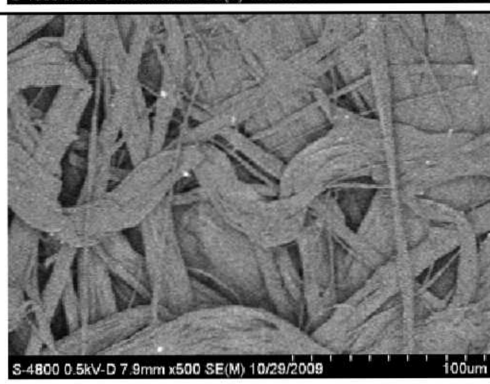
Test Article	Pre-Test Condition	Post Tumbling/Cleaning Condition
#1 - Orthofabric		
#2 – Gore-tex 4 Harness Satin		
#3 – Gore-tex 3x1 Twill		
#4 - Tyvek		

Table 5. Scanning electron microscope images at 500x magnification. *The above table displays SEM images of the four candidate fabrics at 500x magnification before testing and after testing/cleaning.*

As seen in Tables 2-5, Test Articles #1-3 all display a very similar level of damage. In all three test articles, the Gore-Tex fibers are shredded and heavily damaged. In this specific set of images, Test Article #2, the Gore-Tex 4 Harness Satin, looks to have the least fiber damage; however, that does not necessarily stand true across multiple areas of the test article. Being that Test Article #4 is fabricated out of Tyvek, a non-woven fabric, the Test Article #4 images are quite different from those of the woven fabrics. Unlike the woven fabrics, one is unable to see damage to the fibers in the Tyvek images. It is; however, possible to see that the Tyvek structure was significantly altered during the test and it looks almost as if the Tyvek has been stripped of its layering of fibers in the post-test images. This fact can be confirmed in the post test photos, which show the Tyvek material as being severely damaged and stripped away from the test article.

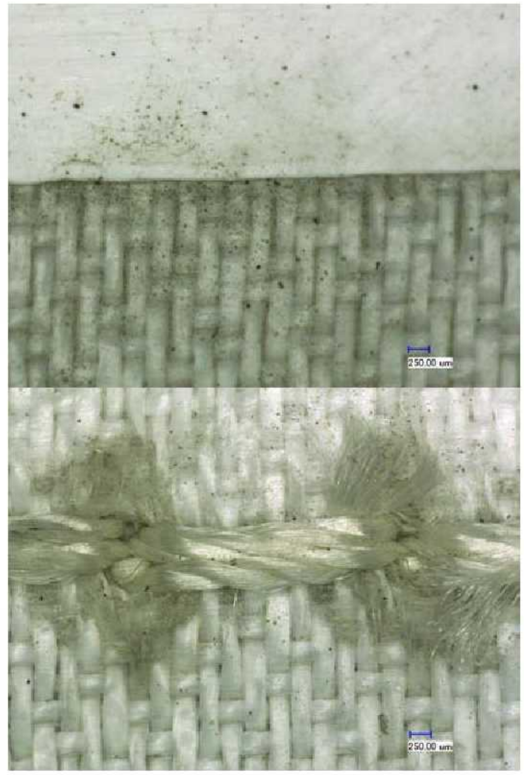


Table 13. Gore-Tex 4 Harness Satin optical images. *The above images display optical microscopy of Test Articles #5 (top) and #3 (bottom), the Gore-Tex 4 Harness Satin fabric with and without heat sealed seams, respectively at 50x magnification.*

While all the SEM images captured were of the outer (exposed) side of the test article, optical microscopy images were also captured of the fabric inner (non-exposed) side. The original idea of this microscopy was to compare dust migration through non-coated versus coated materials, as well as through non-heat sealed versus heat sealed seams. However, as mentioned in the visual inspection section of the test results, abrasion on the end-caps led to holes and subsequent dust migration to the inside of the outer layer in all test articles. It is impossible to discern whether dust on the inside of the outer layer fabric was due to these small holes, migration through the fabric itself, or migration through the seams. Figure 13 provides example optical microscope images of the back side of the Gore-Tex 4 Harness Satin material with and without heal sealed seams. In these images, it actually appears that the material with the heat sealed seam contains more dust particles than the material without the heat sealed seam. As noted above, the additional dust particles may have migrated through one of the small holes on the end cap, rather than through the seam, and there is really no way to discern the correct migration path.

VI. Conclusions

As stated in the Objectives section of this paper, the primary objective of this study was to build on past work and provide a preliminary evaluation of various candidate outer layer fabrics for planetary surface space suit applications. The secondary objectives included comparing abrasive wear produced by two different lunar simulant types and evaluating the ability of heat sealed seams to prevent dust migration through space suit components. The study examined four candidate space suit materials, tumbled with two different lunar simulants, and including test articles with and without heat sealed seams. Post test visual inspections of the various test articles showed that three of the four candidate fabrics held up relatively well throughout the testing. The fabrics that performed well included Orthofabric, the Gore-Tex 4 Harness Satin and the Gore-Tex 3x1 Twill materials. One fabric, the Tyvek soft structure, performed very poorly in comparison with the other candidate materials. The main abrasive wear noted in the visual inspections was small holes on the end-caps of the cylinders. This wear was consistent across all candidate materials, and led to difficulty in comparing dust migration through the various test articles and seam constructions. Pre- and post-test strength of materials measurements demonstrated that Orthofabric was clearly the strongest fabric used in testing, followed by the two Gore-Tex materials, which were similar in strength. For the most part, the Orthofabric and Gore-Tex materials had a similar percent degredation in strength before and after testing. Tyvek was by far the weakest material across all strength measurements. Microscopy showed similar post-test conditions for Orthofabric and the Gore-Tex materials, and similar to the other results, showed Tyvek to have severe degradation.

Conclusions which can be drawn from this effort are that Orthofabric, and both Gore-Tex materials are viable candidate planetary space suit materials. Tyvek, while viable as an option for a disposable outer layer, is not recommended as a durable suit outer layer. For planetary space suit design, further effort needs to be put into investigating and mitigating dust migration through suit components, as the results of the migration objective in this testing were inconclusive.

Acknowledgments

JSC-1 simulant was kindly supplied by J.J. Kosmo (NASA Johnson Space Center). NU-LHT-2C lunar simulant was kindly supplied by Carole McLemore of the Dust Management Project (DMP) Lunar Simulant Development Task Team (Marshall Space Flight Center). The author would like to thank Evelyne Orndoff and Henry Tang (NASA Johnson Space Center Crew and Thermal Systems Division Materials and Softgoods Group) for providing input to the test protocol as well as performing pre- and post-test strength of materials testing on the test articles. Mary Jane O'Rourke (NASA Johnson Space Center Materials and Processes Branch) kindly performed the Optical and Scanning Electron Microscopy. Dana Valish (NASA Johnson Space Center Cooperative Education Student) kindly assisted in performing the test protocol.

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