Development of Advanced Environmental Protection Garments Containing Shear Thickening Fluid Enhanced Textiles (STF-Armor^{TM}) for Puncture Protection and Dust Mitigation

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Environmental protection garments (EPG) containing shear thickening fluid (STF) enhanced textiles can provide multi-functional protection and bridge key EVA suit technology gaps to enable sustainable human exploration missions beyond low Earth orbit. Work completed under a Small Business Technology Transfer Research (STTR) Phase I award and NASA EPSCoR awards at the University of Delaware demonstrated prototype STF-enhanced EPGs that address key technology gaps related to physical hazard protection (i.e. dust mitigation, secondary ejecta/MMOD, puncture) for future crewed exploration missions, including lunar and planetary exploration. STF-textiles have superior flexibility, and thus, have a significant competitive advantage over other puncture-resistant materials, and are amenable to the construction of advanced suits that combine a high level of crewmember protection with high mobility. This paper describes the development and ongoing testing of STF-enhanced EPGs, including physical, thermal, and environmental testing of new STF-enhanced textiles and lay-ups. STF formulations meeting vacuum stability/offgassing requirements were successfully developed and applied to the Orthofabric shell layer and to candidate absorber layer textiles. STF-enhanced EPG layers were shown to have two to three times higher standard puncture force with only 10-30% mass add-on and no change in flexibility as compared to the untreated textiles. New test methods for evaluating the penetration of regolith through EPG layers are presented. The combination of STF and superhydrophobic "lotus leaf" coatings was shown to prevent dust infiltration into the shell fabric and facilitate removal of surface dust. Prototype STF-containing EPG layups developed in the Phase I STTR are scheduled to be flown to the ISS on the Materials on the International Space Station Experiment (MISSE-9) in 2018.

Nomenclature

EMU	=	extra-vehicular mobility unit
EPG	=	environmental protection garment
EVA	=	extra-vehicular activity
ISS	=	International Space Station
LEO	=	low-Earth orbit
MISSE	=	materials on the International Space Station experiment
MLI	=	multi-layer insulation
MMOD	=	micrometeoroid and orbital debris
STF	=	shear thickening fluid

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STF-LV = low-volatility shear thickening fluid
TMG = thermal micrometeoroid garment
TRL = technology readiness level
UHMWPE= ultra-high molecular weight polyethylene

I. Introduction

Improving safety and mission reliability on extended duration exploration missions will require durable environmental protection garments (EPG) that offer enhanced astronaut protection while being capable of withstanding extended use and multiple EVAs. In contrast to Apollo-era suits that were required to perform for only a small number of EVAs, the proposed xEMU and mEMU suits for exploration of the lunar and Martian surfaces will need to function effectively for an extended duration (e.g. 600+ hours or 10^6 walking cycles) and withstand harsher conditions, including handling of sharp or rough rocks, exposure to abrasive regolith, and potential secondary ejecta impacts.[1] Resistance to puncture/cut-puncture is an essential protective attribute of EVA suits that is not well-met by current materials. During EVA on prior STS missions astronauts sustained damage to gloves due to small, sharp edges from MMOD impacts on ISS handrails. This glove damage led to termination of the EVA in some cases.[2,3] Gloves for subsequent missions were reinforced with additional patches to improve protection, but such patches can reduce glove mobility and increase crewmember fatigue.[4,5] The use of stiff or heavy textiles is not a desirable approach for creating more durable suits. Further, rapid replacement or modification of damaged suits will not be possible for future, extended-duration surface missions. Thus, there is an important need for new lightweight, highly flexible, and highly puncture resistant EPG materials.

Mitigation of the hazards posed by regolith (dust) is also an important, unmet feature of current EVA suit technology. The experience reported from Apollo EVA on the Lunar surface revealed the difficulty of conducting successful, long-term operations on the surface of the Moon or Mars in the presence of dust.[6] Substantial damage to suits was observed after only one or two Apollo EVAs, as the Lunar dust proved to be extremely abrasive. Transfer of dust into the vehicle or habitat is also of particular concern for crew health and the long-term operability of equipment, particularly seals and mechanical devices. Suit materials and systems that can withstand repeated surface EVA in a dusty environment while also preventing transfer of dust into the habitat have been identified as critical technology gaps that must be closed in order to enable a sustained human Mars exploration mission.[7]

The research presented in this paper investigated shear thickening fluid (STF) treatment of EPG fabrics as a means for addressing key technology gaps by providing mass-efficient improvements in multiple protection categories while also maintaining a high degree of flexibility. STF treatment of shell and absorber layer fabrics was shown to improve resistance to puncture, cut-puncture, and dust infiltration while maintaining flexibility. The results presented in this paper form a basis for the ongoing continued development and TRL advancement of STF-enhanced EPGs through a STTR Phase II project. A related experiment being led by the University of Delaware affiliated authors is using MISSE-9 to investigate the MMOD resistance and LEO environmental stability of EPG lay-ups containing the STF-enhanced layers described below.

II. Technology Overview

EPGs consist of multiple textile and polymeric layers that combine to provide multi-functional protection to the suited crewmember. Figure 1 shows a conceptual illustration of the locations in the EPG where STF-treated materials are proposed as substitutes for existing materials.

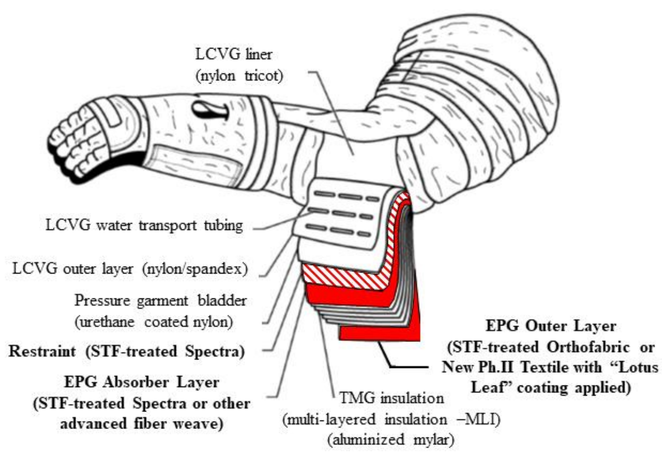

Figure 1. Illustration of space suit layers with STF-enhanced textiles as substitutes for the shell and absorber layers. Image adapted from NASA.

Shear thickening fluids are concentrated suspensions of colloidal particles in a suitable carrier fluid. STFs are flowable and gel-like when subjected to low shear rates, but transition to a solid-like behavior when high shear rates are applied.[8,9] The ability of STFs to behave as a liquid or solid under different conditions lends itself to a number of applications in which rate-sensitive behavior is beneficial. One example, STF-Armor™ that was co-invented with Dr. Eric Wetzel of the US Army Research Laboratory (so-called "liquid body armor" by the press), is a nanocomposite material in which STF is intercalated in between fibrils in the yarns of woven Kevlar®, resulting in a dry, flexible textile that can be subsequently coated, sewn, or treated as needed.[10] The STF-Armor™ textile is as flexible as the base textile, as the intercalated STF has soft gel-like properties at the shear rates associated with normal human movement. When impacted by bullet or fragment traveling at high velocity the STF, which itself is comprised primarily of ceramic nanoparticles, rigidizes into a ceramic-like solid nearly instantaneously at the point of impact to aid in stopping the projectile. STF has been shown to improve resistance to stab and puncture.[11] Further, the intercalation (addition of STF between the filaments of the yarns that comprise the textile) of STF into woven Kevlar® has also been found to improve the flame-resistance of Kevlar®, even when the STF fluid phase was a hydrocarbon oil.[12] The high inorganic particle loading of the STF (up to 80wt%) improves fire retardancy of the treated textile, as evidenced by reduced afterglow and char length in the ASTM D6413 test.

STF treatment enhances the puncture and ballistic performance of Kevlar® or other high strength fibers by restricting the relative movement of adjacent fibers when impacted, keeping the yarns engaged with the projectile and thereby taking full advantage of the high strength-to-weight ratio of high tenacity fibers like Kevlar®, Spectra®, or Vectran®.[13-15] STF-Armor™ materials provide effective protection against small fragments and puncture threats that would otherwise easily penetrate plain woven textiles. EVA suit lay-ups containing an STF-Armor™ absorber layer have also been shown to have improved puncture and MMOD resistance at reduced mass, as compared to current lay-ups.[16]

STF intercalation can provide additional benefits for EPGs beyond the previously demonstrated, mass-efficient enhancement of puncture and ballistic properties of absorber layer fabrics. STF-treatment of the Orthofabric shell intercalates the STF material between the fibers and fills space that would otherwise allow fine dust particles to infiltrate or penetrate the same neat fabric. Therefore, when a STF-treated fabric is exposed to a dusty environment, the bulk of the dust particles will be confined to the surface of the fabric instead of infiltrating into the weave. Preventing infiltration of dust deep into the weave facilitates subsequent removal of dust. Furthermore, the use of superhydrophobic (also called "lotus leaf") coatings on the fabric can provide a degree of self-cleaning functionality for the EPG shell fabric. Such lotus leaf coatings have been demonstrated to provide dust-resistant/self-cleaning functionality on hard surfaces[17] and are attractive for imparting similar self-cleaning properties to the EPG shell fabric. A conceptual illustration of the potential dust mitigation benefits of STF treatment combined with a superhydrophobic coating is shown in Figure 2. Dust that penetrates through the shell fabric and into the deeper layers of the suit can act as an abrasive when adjacent fabric layers or areas are bent during normal suit use. The results presented in the remainder of this paper describe the development of test methods and proof-of-concept testing that showed that STF-enhanced EPG materials can provide mass-efficient, highly-flexible solutions for dust mitigation and enhanced physical hazard protection.

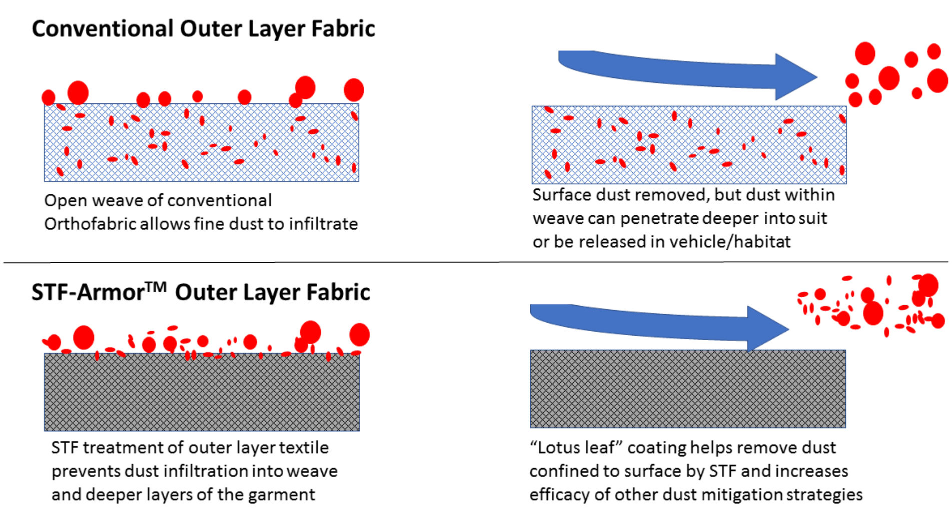

Figure 2. Mitigation of dust infiltration by STF and superhydrophobic treatment of EPG shell layer fabric.

III. Materials and Experimental Methods

A. EPG Fabrics

Orthofabric is the shell fabric that is used in the current TMG. Orthofabric has two distinct faces consisting of Nomex® with a Kevlar® ripstop on the face that is oriented towards the inside of the suit and Gore-Tex® on the externally-oriented face. STF treatment of the Orthofabric offers dual benefits related to the potential improvement in dust resistance as well as the potential increase in puncture resistance.

The addition of STF to the absorber layer textile can potentially increase physical hazard resistance (i.e., puncture, MMOD) of the entire EPG. The coated nylon absorber layer in the current TMG cannot be treated with STF because the neoprene coating prevents any possibility of STF intercalation into the fabric. Additionally, new fiber and weaving technology developed since the original selection of the neoprene coated nylon can potentially be leveraged to improve the absorber layer and overall protection offered by the EVA suit. Candidate textiles were sourced from various suppliers and were evaluated as potential EPG absorber layers. Candidate absorber layers included woven fabrics made from Nomex®, Spectra®, Kevlar®, and Vectran® fibers. A woven Spectra® fabric was downselected for further testing as a potential absorber layer in this study. The downselected Spectra® fabric was originally designed as a restraint layer and performs well in this function. Therefore, we elected to also use STF-Spectra® as a replacement for the previous restraint layer in order to maximize protection against physical hazards. Thus, the current proof-of-concept lay-up contains two adjacent layers of the STF-Spectra® that replace the absorber and restraint layers in the conventional suit lay-up (see Figure 1).

B. Puncture Testing

Resistance to puncture by pointed objects and cut-puncture threats was measured using an Instron 5943 load frame equipped with a 1 kN load cell and puncture test methods based on ASTM F-1342 (puncture) or ASTM F-2878 (cut-puncture) method. A 75mm x 75 mm test specimen was securely mounted in the standard-specified sample holder having 10 mm puncture guide holes. The probe displacement speed was modified from the standard and was 10 mm/min for both tests. The needle used in the cut-puncture test was a 21-gauge hypodermic needle (Becton-Dickinson part #305167) and a new needle was used for each individual puncture test. The puncture force for each test is reported as the maximum force recorded during the test. Eight individual puncture tests were performed on each sample.

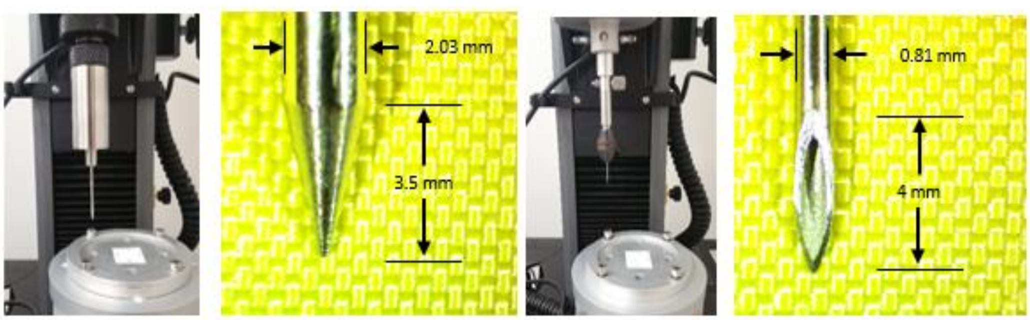

Figure 3. Puncture probe mounting and dimensions for (Left) ASTM F-1342 puncture probe (Right) 21-gauge hypodermic needle used as the ASTM F-2878 cut-puncture probe.

C. Shear Thickening Fluid and Fabric Treatment

Shear thickening fluids for puncture and dust-resistance testing were formulated using silica nanoparticles in low-viscosity silicone-based carrier fluids. Silica nanoparticles are blended into the silicone carrier at a total particle loading of 67 wt% using mixing methods reported by previous authors.[16] STF was intercalated into the Orthofabric and woven Spectra® using the padding process that was been reported previously by Cwalina et al. Briefly, the STF was diluted with ethanol in a volumetric ratio of 2 parts ethanol to 1 part STF. The fabric was immersed in the diluted STF for one minute and then passed through nip rollers to control the amount of STF applied to the fabric. The fabric was dried in an oven for one hour at 70 ºC to remove the ethanol. Fabric weight was recorded before and after treatment and the areal density was calculated. Treatment of fabrics using the STF-LV formulation used 1-pentanol as the diluent instead of ethanol. STF treatment did not significantly alter the flexibility compared to the untreated fabric.[10]

A commercially available superhydrophobic coating was obtained from Hydrobead (San Diego, CA). Hydrobead is an aerosol-applied coating that leaves a nanostructured surface that imparts the superhydrophobicity. The Hydrobead coating was applied to both sides of the Spectra® fabrics. Two coats of Hydrobead were applied according to manufacturer's instructions. The Gore-Tex face of the Orthofabric is non-wetting and the superhydrophobic coating could not be successfully applied. The Nomex®/Kevlar® face of the Orthofabric was treated with the superhydrophobic coating for the dust removal trials.

D. Characterization of Dust Resistance

Resistance to dust was evaluated using two different methods, each intended to simulate different methods of dust exposure and test different aspects of dust mitigation. The first method used a Taber abraser and fabric coated wheel to simulate flexion or rubbing of adjacent fabric areas in the presence of dust. This method visualizes the amount of simulant that can penetrate through the fabric and potentially act as an abrasive once inside the suit. The second method completely immersed the fabric specimen in simulant to simulate the exposure of a portion of the suit (e.g., boot or leg) to large amounts of dust. Following immersion, a pressurized air jet was used to investigate the ease of removing the dust. The immersion and removal test is intended to evaluate the effects of STF and superhydrophobic coating on the ease of cleaning regolith from the surface of the suit, for example, prior to re-entry into the vehicle or habitat.

The Mars regolith simulant used to investigate the dust mitigation properties of the newly developed materials was JSC Mars-1A. JSC Mars-1A simulant was obtained from Orbital Technologies Corporation (Madison, WI). The simulant is a palagonitic tephra with a typical particle size of 1mm or smaller. The complete particle size distribution and elemental composition of the JSC Mars-1A simulant are available from the supplier.

The ability of various fabrics to resist dust infiltration was characterized using a newly developed, custom test method. The test is based on a Taber abraser and uses fabric-on-fabric abrasion in the presence of dust to evaluate penetration. The test is intended to simulate adjacent portions of the fabric rubbing together in the presence of dust. An approximately 3" circular test specimen is placed on top of a piece of witness paper and clamped into the abraser sample holder. A strip of the same fabric is cut and attached to a Taber CS-0 rubber wheel using adhesive. JSC Mars-1A simulant (0.3g) is spread evenly around the sample in the abrasion path. The abraser test is then run for 10,000 cycles at a speed of 72 rpm. The red color of the Mars simulant has good contrast with the white witness paper and the amount of dust that penetrates the fabric can be qualitatively determined by observing the intensity of the red color on the witness paper after the test. Similarly, the amount of simulant that is deposited within the white-colored Orthofabric or Spectra® can easily be visualized.

A second test method was used to investigate how the STF and superhydrophobic coating influences dust infiltration and ease of dust removal after complete immersion in dust. The effectiveness of the superhydrophobic coatings were evaluated using a method adapted based on prior testing at Goddard Space Flight Center by O'Connor.[17] A 75 mm x 75 mm test specimen of the fabric was placed in a 150mm circular crystallizing dish containing 50 grams of JSC Mars-1A simulant. The specimen was gently positioned to completely immerse the fabric in simulant. The dish was oscillated laterally by hand for 1 minute. After the 1-minute agitation the sample was removed, gently tapped to remove very loosely adhered simulant, and photographed. The samples were then exposed to a compressed air jet for 30 seconds and photographed again.

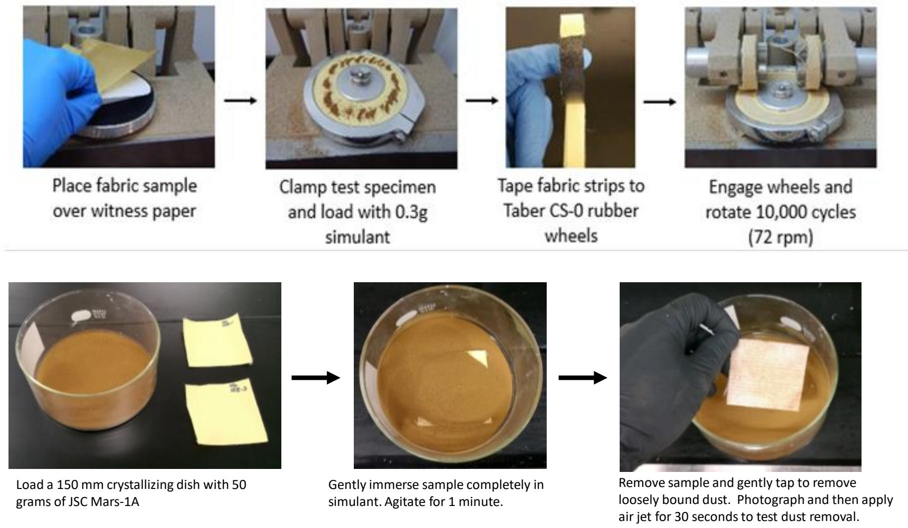

Figure 4. Two types of dust penetration tests used to evaluate the dust mitigation efficacy of STF and superhydrophobic treatments. (Top) Fabric-on-fabric dust penetration test (Bottom) Dust immersion and cleaning test.

IV. Results and Discussion

Both the Orthofabric and Spectra® fabric were successfully treated with STF. The absolute and relative increases in weight following STF treatment are listed in Table 1. The Orthofabric has a high weight and open weave relative to the Spectra® and other candidate absorber layer fabrics, which are typically about 250 g/m^2 or less. Therefore, the absolute STF uptake for Orthofabric is much higher than that for the lighter, absorber layer fabrics. Observations of the Gore-Tex® face of the Orthofabric suggest that the STF is not effectively intercalated into the Gore-Tex®, meaning that only the space within the Nomex® and Kevlar® yarns is available for intercalation of STF. In contrast, the entire yarn structure of the Spectra® can be intercalated with STF and the relative increase in weight with treatment is higher.

Table 1. STF Add-on for Spectra®, and Orthofabric

	Neat Weight (g/m^2)	**Post-treatment Weight (g/m^2)**	**Absolute Weight Increase (g/m^2)**	**% Increase in Weight**
Orthofabric	518	623	105	20
Spectra®	194	252	58	30

E. Puncture and Cut-Puncture Resistance

The resistance to puncture was measured for the Orthofabric and the Spectra® absorber layer fabric. Treated and untreated fabric specimens were subject to puncture force analysis using an ASTM-F1342 probe and the method described in Section III. The box plots in Figure 5 summarize the test results on each sample as follows: the small square in each box is the mean puncture force, the height of the box represents one standard deviation above and below the mean, the whiskers indicate the maximum and minimum recorded puncture force, and the horizontal line in the middle of the box is the median. The addition of STF to the Orthofabric increased the average puncture force by nearly 250% for a weight add-on of only 20%. Further evidence of the efficacy of the STF treatment is shown by the box plot in Figure 5 - the minimum force to puncture the STF-treated Orthofabric exceeds the maximum force to puncture the neat Orthofabric. This is an indication that the intercalation of the STF changes the failure mode during puncture from a windowing mode in the untreated fabric (i.e. the probe is able to slip between fibers/yarns) to a breakage mode for the STF-treated fabric. The energy required to break yarns is substantially higher than the energy required to puncture via windowing and a commensurate increase in puncture resistance is observed.

Table 2. ASTM F-1342 Probe Puncture Forces for Neat and STF-Treated Materials

	Force to Puncture Neat (N)				Force to Puncture STF-treated (N)				
	Average	Max.	Min.	Std. Dev.	Average	Max.	Min.	Std. Dev.	% Increase in Avg. Puncture Force with STF Treatment
Spectra®	20.5	22.8	17.5	1.5	46.2	50.8	39.2	3.6	125
Orthofabric	8.5	9.7	6.8	1.0	29.5	33.4	26.9	2.1	246

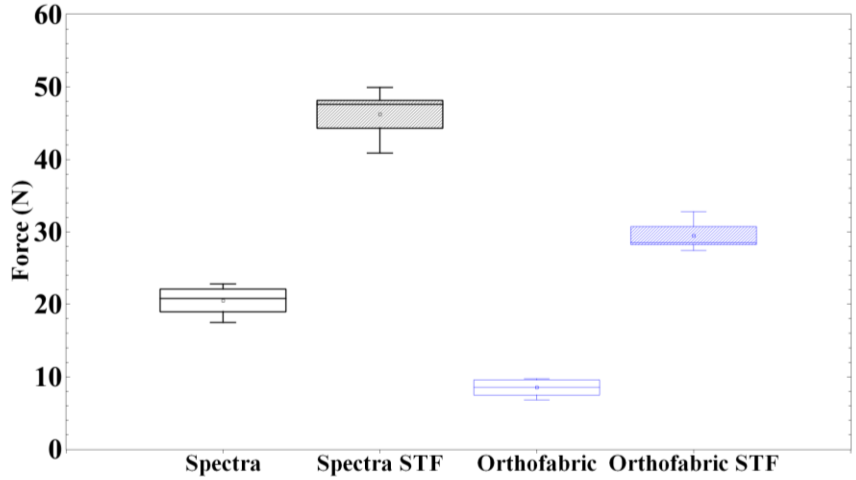

Figure 5. Results of puncture testing using ASTM F-1342 probe.

Test results for the resistance of each fabric to cut-puncture are summarized in Figure 6. The hypodermic needle is a highly-effective cut-puncture threat and the overall forces are significantly lower than the forces measured for the F-1342 probe. Despite the aggressive cut-puncture threat, the STF treatment is still effective at providing a mass-efficient increase in puncture resistance. The STF treatment provided a larger increase in puncture force for the Spectra® fabric than the Orthofabric in both absolute and relative terms. This is attributed to the higher intrinsic cut resistance of the UHMWPE Spectra® fibers as compared to the Nomex® that makes up the bulk of the treated portion of the Orthofabric. Although the STF likely suppresses windowing in the Orthofabric, the bevel can still cut through the Nomex® fibers with relative ease and the benefits of changing the puncture mode from windowing to cut/breakage are limited by the low cut resistance. In contrast, when the STF acts to prevent the needle from slipping between Spectra® fibers the needle must instead cut the tough UHMWPE fibers to penetrate. The efficacy of changing the failure mode is further illustrated by the box plot shown in Figure 6. The Spectra® results show that the minimum puncture force for the STF-treated Spectra® exceeds the maximum for the untreated Spectra®. The box whiskers overlap on the plot for the Orthofabric, which suggests some similarities in the mixed puncture modes for the treated and untreated variants.

Table 3. Summary of Cut-Puncture Results for Spectra®, Kevlar®, and Ortho Fabric

	Force to Cut-Puncture Neat (N)				Force to Cut-Puncture STF-Treated (N)				
	Average	Max.	Min.	Std. Dev.	Average	Max.	Min.	Std. Dev.	% Increase in Puncture Force with STF Treatment
Spectra®	1.3	1.7	1.1	0.3	2.5	3.2	2.1	0.4	88
Orthofabric	0.89	1.2	0.5	0.2	1.4	1.7	1.1	0.2	54

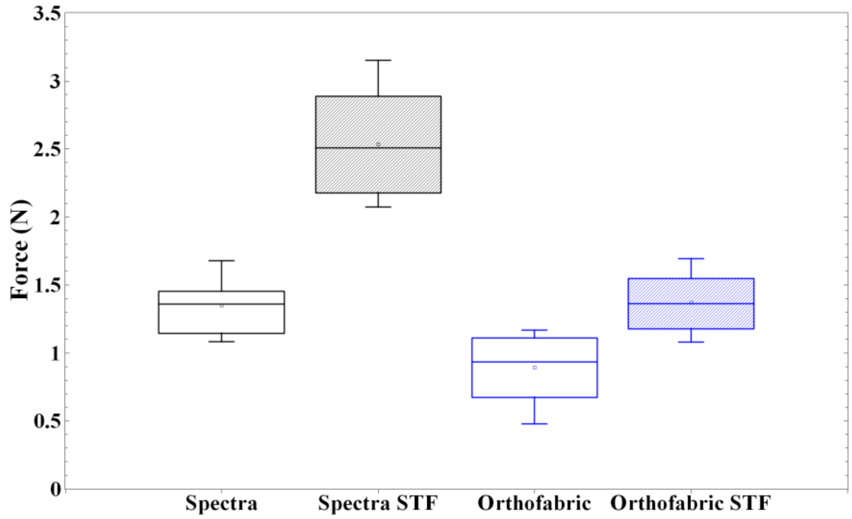

Figure 6. Results of cut-puncture testing using ASTM F-2878/21-gauge hypodermic needle.

The puncture and cut-puncture test results indicate that STF treatment is a mass-efficient means for improving the puncture and cut-puncture resistance of Orthofabric and a woven Spectra® candidate absorber layer. The mass-normalized puncture forces are summarized in Table 4. STF treatment increased the puncture force by a factor that is higher than the weight increase, thereby providing further evidence that the STF treatment is effective at changing the puncture mode for these materials. The *minimum* mass-normalized puncture force for the STF materials typically exceeds the *maximum* normalized force to puncture the neat fabrics. Thus, the STF-treated materials offer engineering solutions that can offer increased puncture force at equal weight, or alternatively, offer the opportunity to design highly protective EPGs that are thinner, lighter, and/or more flexible than the current state-of-the-art.

Table 4. Mass-Normalized Puncture Forces

	Average Puncture Force per Fabric Weight [N/(g/m^2)]		**Average Cut-Puncture Force per Fabric Weight [N/(g/m^2)]**	
	Neat	STF-Treated	Neat	STF-Treated
Spectra®	0.11	0.18	0.0071	0.010
Orthofabric	0.016	0.047	0.0017	0.0022

F. Dust Resistance

The results of the rotary, fabric-on-fabric dust penetration testing on the neat and STF-treated Orthofabric are shown in Figure 7. As noted previously, the Orthofabric weave is relatively open and can allow the simulant particles to penetrate through the fabric. After 10,000 rotations of the abraser there is significant discoloration due to simulant deposition all along the fabric-on-fabric wear path on the Orthofabric face. Micrographs show that a significant amount of simulant is embedded within the Orthofabric. Furthermore, the witness paper that was below the test specimen is discolored from simulant deposition over the entire wear path. These results indicate that during suit use in a dusty environment the dust would be expected to easily infiltrate the Orthofabric weave and will be embedded or carried through the weave by repeated motion/flexion. The embedded regolith can abrade the Orthofabric and any regolith that is carried through the weave can abrade the MLI below the Orthofabric. In contrast, the STF-treated Orthofabric has significantly less discoloration along the fabric-on-fabric wear path (Figure 7, bottom row). Inspection of the surface under the microscope clearly shows that the simulant was not able to work deeply into the weave. This is confirmed by the inspection of the witness paper, which shows only very minor discoloration in four small areas, as indicated by the red circles in Figure 7. The dust penetration test results on the STF-treated Orthofabric indicate that the space-filling provided by STF intercalation into the fabric can effectively function to prevent dust from infiltrating into/through shell fabric materials. Such mitigation of dust infiltration can reduce intra- and inter-layer abrasion in the presence of dust, potentially extending the usable lifetime of a suit in a dusty environment.

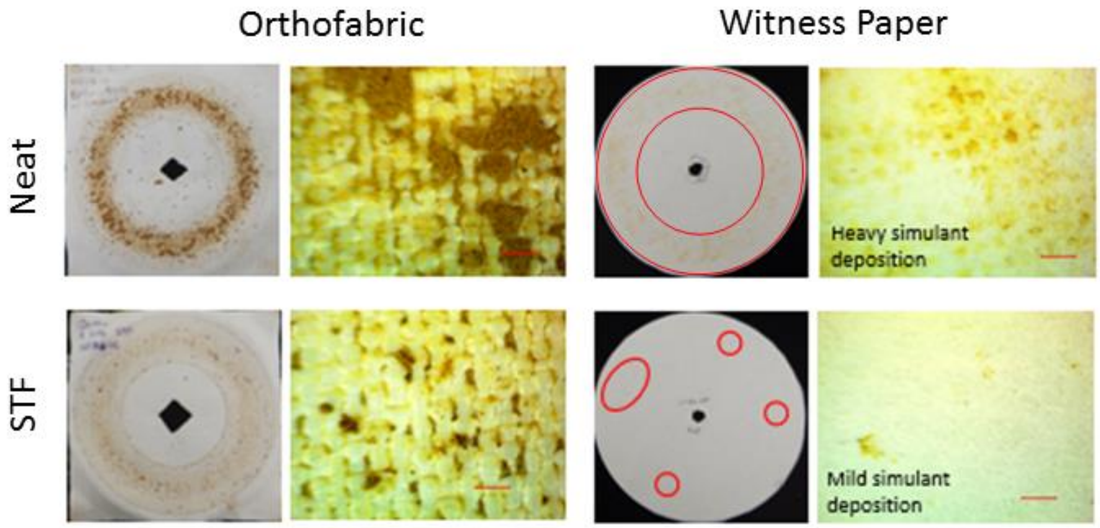

Figure 7. Results of fabric-on-fabric dust penetration testing on neat and STF-treated Orthofabric. Areas circled in red on the witness paper indicate areas where visible simulant deposition was observed, indicating that the simulant was able to penetrate through the fabric. Simulant deposition was observed throughout the contact path for the neat Orthofabric. Only minor simulant deposition was observed in a few areas on the witness paper for the STF-treated specimen.

Having shown that the STF intercalation can limit dust to the surface of the shell fabric, additional dust immersion testing was performed to determine potential benefits for cleanability and whether the STF treatment can be combined with other dust mitigation strategies to facilitate dust removal prior to crewmember re-entry into a vehicle or habitat. The superhydrophobic Hydrobead was selected as a softgoods-compatible analog to the "lotus leaf" coatings used in the prior self-cleaning studies.[17] The results of simulant immersion testing on the Orthofabric and Spectra® are shown below in Figures 8 and 9, respectively. The Gore-Tex® surfaces of the neat and superhydrophobic coated Orthofabric did not exhibit a significant difference in appearance after the air jet dust removal. It is believed that the Hydrobead coating does not effectively bind to the Gore-Tex® and the treatment does not significantly alter the Gore-Tex® face. Observation of the reverse side of the Orthofabric (Figure 8) shows that the superhydrophobic coating leads to an apparent reduction in the amount of simulant deposited on the fabric directly after immersion and appears to facilitate removal of the simulant by the air jet.
There is less discoloration of the superhydrophobic treated specimen compared to the untreated specimen after both steps in the testing. One potential limitation of the test method when evaluating single fabric layers is that the air jet

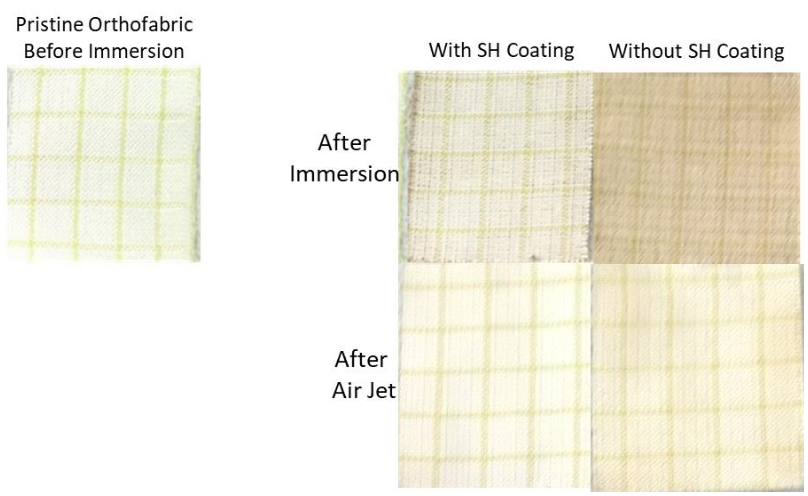

Figure 8. Dust immersion testing showing the reverse side of the Orthofabric with and without superhydrophobic coating (no STF).

can push simulant through the open weave of the Orthofabric instead of removing it directly from the surface. In an EPG application, the layers beneath the shell would act to prevent removal by such a method. Nonetheless, the results of the simulant immersion testing indicate that the dust-resistant superhydrophobic coating concept that has previously been shown for hard surfaces can potentially be adapted to softgoods.

The simulant immersion test results shown in Figure 9 illustrate the efficacy of the superhydrophobic coating in facilitating dust removal. Although the Spectra® is being considered as an absorber layer in the current study, the tighter weave provides a useful basis to investigate how new shell layer fabrics having a construction that is thinner and denser than the Orthofabric could improve dust mitigation. The neat Spectra® is significantly discolored by the simulant both after immersion and air jet steps. The superhydrophobic coating alone acts to substantially reduce the amount of simulant deposited on the Spectra® after immersion and most of the simulant is removed from the coated sample by the air jet (second row in Figure 9). An intermediate result was observed for the sample treated with both the STF and superhydrophobic coating. After immersion the sample was discolored, but the air jet was able to remove nearly all of the simulant and only very slight discoloration remained. The post-immersion discoloration may be attributable to a poorer quality superhydrophobic coating when it is applied over the top of an STF treated textile compared to a neat textile. Alternatively, the STF itself may act to loosely bind the simulant. Further characterization of the coating quality and surface wetting properties are needed to conclusively determine which mechanism is responsible for the higher degree of discoloration compared to the sample treated with only the superhydrophobic coating. The combined immersion testing results do conclusively indicate that the combination of STF and superhydrophobic coating can act to keep dust near the surface of the fabric where it can then be removed by an appropriate method.

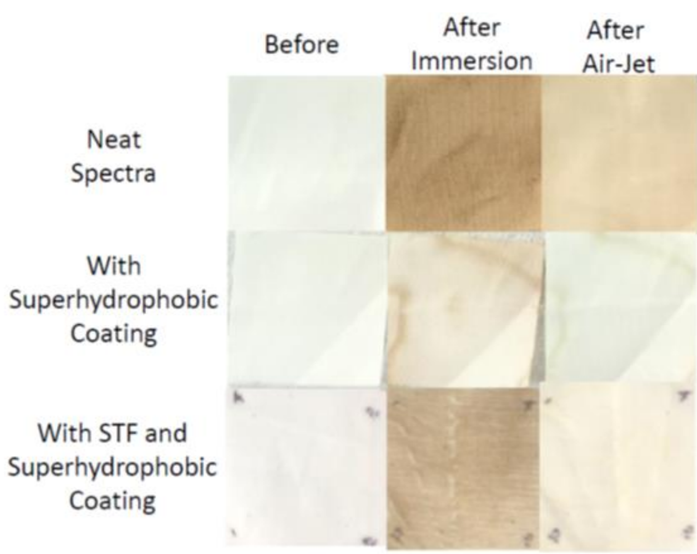

Figure 9. Results of simulant immersion and removal testing on woven Spectra® fabric

G. Continuing Developments and ISS Experiments

A low-outgassing STF formulation (STF-LV) was developed using a low-volatility, hydrocarbon-based carrier fluid to prove that the formulation can be adjusted to meet outgassing[18], thermal, and other requirements while maintaining the physical hazard protection and dust resistance benefits of STF treatment. Prototype EPG lay-ups containing Orthofabric and Spectra® absorber layers treated with the STF-LV formulation have been produced and delivered for testing on the MISSE-9 experiment, where the materials will be exposed to the LEO environment and tested upon return. This University of Delaware led MISSE research is also performing ground-based testing to measure the optical properties of STF-LV Orthofabric and gauge the effects of atomic oxygen exposure on the puncture and MMOD resistance of the prototype lay-ups.

V. Conclusion

The application of a shear thickening fluid treatment to EPG shell fabric was shown to provide mass-efficient improvements in puncture and dust resistance while maintaining a high degree of flexibility. The combination of a superhydrophobic coating and shear thickening fluid treatment was shown to improve resistance to dust infiltration and facilitate removal of dust from candidate EPG fabrics. Ongoing work to advance the TRL of these new EPG materials includes the development of low-outgassing, LEO-stable STF formulations, MISSE and ground-based testing, and optimization of the shell layer and absorber layer fabric materials and structures.

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