Development and Evaluation of a Woven-Nonwoven Hybrid Environmental Protection Garments (EPG) Shell Textile for Lunar Exploration Mission

Michelle Yatvitskiy, Huantian Cao, Norman Wagner, University of Delaware, USA
Richard Dombrowski, Erik Hobbs, STF Technologies LLC, USA
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A big challenge for future lunar exploration missions is developing an Environmental Protection Garment (EPG) Shell capable of withstanding extended usage (Gaier et al., 2009) while meeting extreme temperature, radiation, and regolith requirements. The EPG shell must withstand lunar surface temperatures from -178°C to -233°C (Flores-Daley & Jones, 2022), be durable over hundreds of hours of VUV radiation exposure without reducing its functionality (SBIR/STTR, 2023), and withstand extreme abrasion from regolith dust (Gaier et al., 2012). The current EPG shell is Orthofabric: a two-layer plain weave with Goretex on the face and Nomex and Kevlar on the back. Orthofabric's woven structure with intra-yarn gaps allows dust penetration and voids in the face increases dust adhesion (Dombrowski et al., 2022), making it unsuitable for extended Lunar exploration missions. Needle punched nonwoven fabrics have the potential to withstand the extreme requirements on the moon. By altering the fabric composition and adding a scrim support, nonwovens can be abrasion resistant, breathable, dust free, tear resistant, flame retardant and high temperature resistant (Yilmaz et al., 2020).

The purpose of this research is to develop a nonwoven-woven hybrid fabric that can be used for future EPG shells and evaluate the fabric's dust resistance and strength performance before and after radiation exposure. As depicted in Figure 1 to create the hybrid fabric, the researchers carded 4g of P84® polyimide fibers (Evonik Industries, Essen, Germany) 8 times on a Strauch Drum Carder to create a batt. The 4g batt was then split into two 2g batts and each batt was carded 2 more times. The Vectran Orthofabric (a modification of Orthofabric with Nomex fibers replaced with Vectran) was cut into a 10"x20" rectangle and the two batts were placed on the back of the Vectran Orthofabric, one vertical and one horizontal creating a two directional fiber layup. The materials were then felted using a FeltLOOM® needle-punching machine. The batt and fabric were felted 2 times where the fiber batt side was facing up and then 38 times with the Vectran Orthofabric side facing up to minimize the fuzziness of the P84® on the Hybrid fabric surface. The Hybrid fabric was then calendared at 100˚C using a die press, compressed at 100 psi for 3 minutes to decrease thickness and increase uniformity, and singed and/or razored to remove the P84® fibers from the surface of the Vectran Orthofabric.

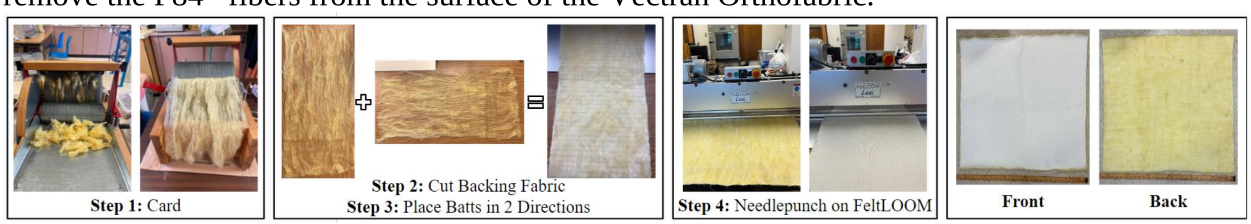

Figure 1. *Hybrid Fabric Development Process*

The researchers tested total dust burden (dust penetrated + dust adhered) and durability properties (flex and abrasion resistance before and after UV radiance exposure) for the 3 fabrics: Orthofabric, Vectran Orthofabric, and the Hybrid. The dust test was performed using a sieve shaker dust testing method as described in (Dombrowski et al., 2022). All samples were conditioned at 21°C and 65% relative humidity in accordance with ASTM D1776 method before the abrasion resistance test. The textiles were placed in a Suntest XLS+ (Atlas Material Testing Technology, Mt. Prospect, IL) for 336 hours and a dosage of 462642 kJ/m^2 to simulate extraterrestrial UV exposure. Flex and abrasion resistance was measured before and after UV exposure using a Universal Wear Tester (SDL Atlas, Rock Hill, SC) following ASTM D3885 standard (8lb used on the back and 2lb on the front rack) with four replications. Data was analyzed using independent sample two-tailed t-tests and one-way ANOVA test.

When analyzing total dust burden, there was a significant difference ($p < .001$) among the 3 fabrics (Mean dust burden: Orthofabric = 163.99 g/m^2, Vectron Orthofabric = 165.01 g/m^2, Hybrid = 63.36 g/m^2). Post-hoc comparisons using Tukey HSD test indicated Orthofabric and Vectran Orthofabric has no significant difference in total dust burden ($p = .866$), however they were significantly different and greater than Hybrid ($p = .002$). Hybrid had no dust penetration unlike Orthofabric and Vectran Orthofabric, but all 3 samples had dust adherence.

Table 1. *Flex and Abrasion Resistance of Fabrics: Before and After Solar Radiance Exposure*

Fabric Type	Before Exposure		After Exposure		T-Test	% Reduction after Exposure
	Mean (cycles)	SD (cycles)	Mean (cycles)	SD (cycles)	P-Value Two-Tail	
			Warp Direction			
Orthofabric	14374.5	2594.05	9886.75	2259.87	0.035	-31.22%
V-Ortho	26241.25	3646.02	7901.5	356.82	< 0.0001	-69.89%
Hybrid	22216.5	1991.84	7798.75	744.3	< 0.0001	-64.90%
			Filling Direction			
Orthofabric	11235.5	2291.21	13720	2005.72	0.15	22.11%
V-Ortho	30968.5	853.68	16037.25	2717.54	< 0.0001	-48.21%
Hybrid	31989	2485.1	20643.25	1340.29	0.0002	-35.47%

The results of flex and abrasion resistance tests before and after solar radiance exposure are in Table 1. Before solar exposure, there was a significant difference among the 3 fabrics in flex and abrasion resistance for both warp and filling directions ($p < .001$). Post-hoc comparisons indicated Hybrid was not significantly different from Vectran Orthofabric (p = 0.165) but significantly different and greater than Orthofabric ($p < .001$) for warp direction; Hybrid fabric was not significantly different from Vectran Orthofabric (p = 0.760) but significantly different and greater than Orthofabric (p < .001) for filling direction. The t-test results indicated that for all 3 fabrics there was a significant difference and decrease in flex and abrasion resistance for warp direction after solar exposure compared to before solar exposure. In the warp direction, Vectran Orthofabric and Hybrid had the biggest % reduction (-69.89% and -64.90%) while Orthofabric had the least % reduction (-31.22%). For the filling direction, Orthofabric's flex and abrasion increased 22.11% after solar exposure but the difference was not significant (p = 0.15). For both Hybrid and Vectran Orthofabric there was a significant decrease in flex and abrasion for filling direction (p < .01, -35.47% and -48.21%). ANOVA results indicated that after solar exposure there was no significant difference in the warp direction ($p = .080$), but there was significant difference in the filling direction ($p = .004$) among the 3 fabrics. The post-hoc comparisons indicated Orthofabric and Vectran Orthofabric are not significantly different from each other ($p = 0.310$) but are significantly smaller than Hybrid ($p = .003$) in the filling direction.

In conclusion, the Hybrid fabric has lower total dust burden than Orthofabric and the Hybrid has no dust penetration. Hybrid fabric has a stronger flex and abrasion resistance than Orthofabric in both warp and filling directions before solar exposure. After solar exposure, Hybrid fabric's flex and abrasion resistance is similar in the warp direction but is a stronger in the filling direction than Orthofabric. The Hybrid fabric is both stronger and better for dust resistance than Orthofabric and has the potential for future EPG shell application.

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