Artemis Suit Material Effects of Calendaring Woven Fabrics on Dust Resistance

Robert J. Jones[1]
Leidos / KBR HHPC / NASA Johnson Space Center, Houston, TX, 77058

Shane McFarland[2]
Aegis Aerospace / KBR HHPC / NASA Johnson Space Center, Houston, TX 77058

Stephanie Rodgers-Ahnen[3]
Textile Made, Inc., Howell, MI 48843

Colton Peabody[4]
Barrios / Amentum Technology / NASA Johnson Space Center, Houston, TX, 77058

and

Felix Arwen[5]
Nexus Solutions / Amentum Technology / NASA Johnson Space Center, Houston, TX, 77058

This paper presents one element of an ongoing NASA technology-infusion effort to design, fabricate, and test a new outer shell fabric for a lunar Extravehicular Activity (EVA) space suit, a critical component of sustained lunar exploration. A primary challenge for suit textiles is preventing lunar dust, which is highly abrasive, electrostatically charged, and capable of infiltrating even tightly woven fabrics from penetrating the Environment Protection Garment (EPG) and compromising suit durability and astronaut safety. To enhance dust-blocking performance, the Artemis Suit Materials Team investigated calendaring, a continuous roll to roll mechanical finishing process in which fabric passes through heated rollers under high pressure to compress and flatten the weave, thereby reducing pore size and modifying surface texture without significantly affecting other properties. Targeted testing of calendared Teflon™ T-162 and Ortho Fabric samples provides new insight into how calendaring influences dust resistance, informing future material development and advancing EVA suit technology for long-duration lunar missions.

Acronyms and Nomenclature

AML	=	Advanced Materials Laboratory
ASM	=	Artemis Suit Materials
ASTM	=	American Society for Testing and Materials
EMU	=	Extravehicular Mobility Unit
EPG	=	Environmental Protection Garment

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[1] Space Suit Engineer, Crew and Thermal Systems Division, NASA Johnson Space Center, Houston, TX.
[2] Technology and Development Lead, Crew and Thermal Systems Division, NASA Johnson Space Center, Houston, TX.
[3] Textile Engineer, Textile Made, Howell, MI.
[4] Space Suit Test Engineer, Crew and Thermal Systems Division, NASA Johnson Space Center, Houston, TX.
[5] Lead Space Suit Fabricator, Crew and Thermal Systems Division, NASA Johnson Space Center, Houston, TX.

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EVA = Extravehicular Activity
ePTFE = Expanded Polytetrafluoroethylene
NCSU = North Carolina State University
PTFE = Polytetrafluoroethylene
Tg = Glass Transition Temperature
TMG = Thermal Micrometeoroid Garment

I. Introduction

ONE of the greatest challenges for exposed textiles used on the lunar surface is their ability to effectively block lunar dust from penetrating into the inner, more sensitive layers of the suit's Environment Protection Garment (EPG). Lunar regolith is highly abrasive, electrostatically charged, and capable of infiltrating even tightly woven fabrics[1], posing risks to both suit durability and astronaut safety.

One potential method to improve a fabric's resistance to dust penetration is calendaring. Calendaring is a mechanical finishing process that involves passing fabric between heated rollers under high pressure. Depending on fiber type and weave, this process can compress and flatten the fabric, reducing pore size and altering the surface texture[2], which this paper asserts can enhance its barrier properties without significantly impacting other metrics. To evaluate the impact of calendaring on dust resistance, the Artemis Suit Materials Team (ASM) conducted targeted testing on calendared samples of Ortho Fabric and Teflon™ T-162.

II. Fabric Summary

The following fabrics were tested in this effort:

Table 1: Fabrics used in study

Fabric Name	Part Number	Manufacturer	Fiber Type	Yarn Denier	Construction	Count
Ortho	116	FDI	Face: ePTFE Back: Nomex w/ Kevlar ripstop	400d ePTFE/ 200d Nomex / 400d Kevlar 29	2-layer basket weave	Face: 52 x 39 Back: 41 x 33
Teflon™	T-162	Stern & Stern	PTFE	400d	Single layer plain weave	78 x 66

Both fabrics are used as outer cover shell fabrics on the Extravehicular Mobility Unit (EMU) Thermal Micrometeoroid Garment (TMG). Ortho Fabric is the primary fabric covering most of the suit (hard upper torso, primary life support system, helmet, shoulders, arms, brief, legs, boots, and glove gauntlets). Only the backs and gauntlet of the Phase VI gloves utilize Teflon™ T-162 however, similar Teflon™ was also utilized in some locations on the Apollo suit TMG. Because of their legacy use, both Ortho Fabric and Teflon™ T-162 are also highly relevant to ongoing lunar suit development efforts.

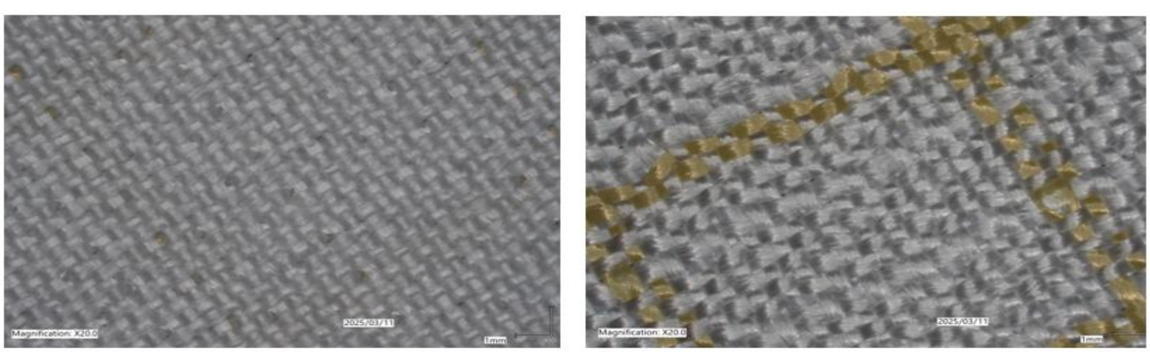

Figure 1. Ortho Fabric. *(Left) Ortho Face at 20x magnification. The Gore-Tex® yarns are white. (Right) Ortho Back at 20x magnification. The Nomex® yarns are white and the Kevlar® ripstop yarns are gold.*

Neat (unmodified) Ortho Fabric (Figure 1) has an areal weight of 15.0 oz/yd^2 (0.509 kg/m^2) and a thickness of 0.027 in (0.69 mm). The outer layer is made from slit fiber expanded polytetrafluoroethylene (ePTFE) commonly referred to by its trade name, Gore-Tex®. The back layer of the cloth is made from Nomex® and Kevlar® yarns. The Gore-Tex® comprises 50% of the fabric, the Nomex®, 45% and the Kevlar® 5%[3].

The yarn count is 51×41 on the face, and 39×33 on the back. There are two-end repeats of Kevlar® 29 yarn after every sixteen Nomex® yarns in both the warp and fill directions to create a ripstop construction[4].

Neat Teflon™ T-162 (Figure 2) is a plain-woven cloth and has an areal mass of 8.2 oz/yd^2 (0.232 kg/m^2) and a thickness of 0.008 in (0.203mm). It is entirely made from polytetrafluoroethylene (PTFE) fibers. It is a lightweight, white fabric.

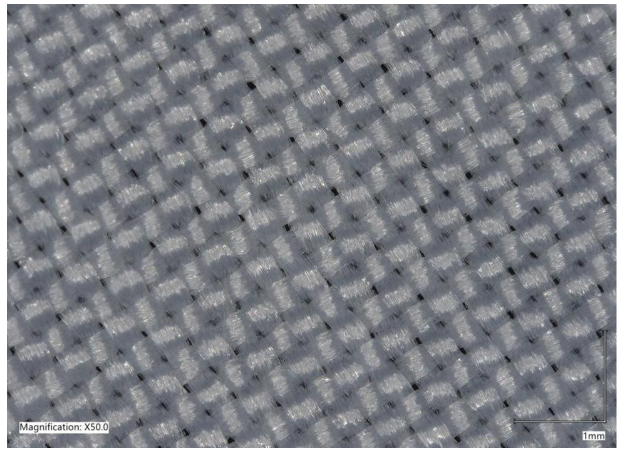

Figure 2. Teflon™ T-162 Fabric. *At 50x, plain woven and made from PTFE fibers.*

III. Calendaring Parameters

Calendaring is a mechanical textile finishing process in which a fabric is passed through one or more high-pressure rollers, commonly called calendar rolls or nips, which may be heated. Calendaring is used for surface smoothing as it reduces fiber protrusion. It compresses the fabric structure, reducing caliper and void volume. It lowers air and particle penetration by closing inter-yarn gaps. Depending on the polymer fiber type, it can also alter the optical properties by changing gloss, reflectance and apparent color to a minor degree[5].

Process variables which can be controlled to produce varying results include nip material, nip temperature, nip pressure, line speed and number of nips. In technical textiles, calendaring can enhance durability, reduce permeability, and also improve coating performance if one is present[6]. Thermoplastic polymers, like Gore-Tex®, can soften and flow under proper conditions and will show a much stronger response to calendaring as opposed to high crystallinity fibers such as Kevlar® and Nomex® that remain dimensionally stable at temperature[7].

Practically, calendaring should be treated as a fiber-system specific process and a one-setting-fits all approach is not warranted. When the main structure is an aramid, the optimal settings aim to control compaction without over-heating, preserving tensile and flex performance. When a flow-capable polymer fiber is present or dominant, the optimal calendaring settings more directly targets controlled softening/consolidation to maximize smoothness, compaction, and dust/air barrier performance. It is important to also avoid overheating which can cause surface smearing, gloss nonuniformity, or adhesion artifacts[5].

For this effort, unmodified Ortho fabric was shipped to the Wilson College of Textiles at North Carolina State University (NCSU) for calendaring. In round 1 testing, calendaring was performed at 419°F (215°C), at a rate of 4.92 ft/min (1.5 m/min), with a nip pressure of 725 psi (50 bar). The resulting fabric is shown in Figure 3. The face of the

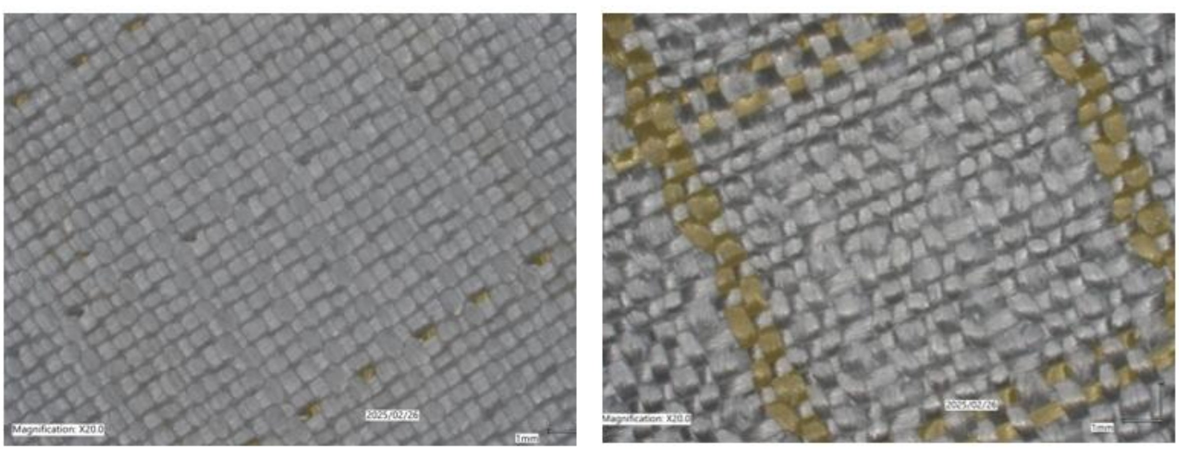

Figure 3. Calendared Ortho Fabric. *(Left) Calendared Ortho Face at 20x magnification. (Right) Calendared Ortho Back at 20x magnification.*

fabric appears to be slightly modified with flatter, more compact whales and smaller interstices. The back appears to be similar to the unmodified version.

For reference, PTFE/ePTFE has a glass transition temperature (Tg) of approximately 239°F (115°C) and a melting point of approximately 620°F (327°C)[8,9]. Nomex®, located on the back, does not melt but begins to decompose at approximately 698°F (370°C)[10]. Kevlar®, the ripstop yarn, also does not melt but decomposes at approximately 842-932°F (450-500°C)[11,12].

Therefore, calendaring at 215 °C places the process well above ePTFE's Tg but safely below its melt temperature. In this regime, ePTFE does not truly melt or flow. Instead, it exhibits significant viscoelastic softening, creep, and chain mobility. Under pressure provided by the nip roller, this allows the PTFE phase to rearrange, conform, and consolidate without risking gross melt flow, loss of dimensional stability, or significant property reduction.

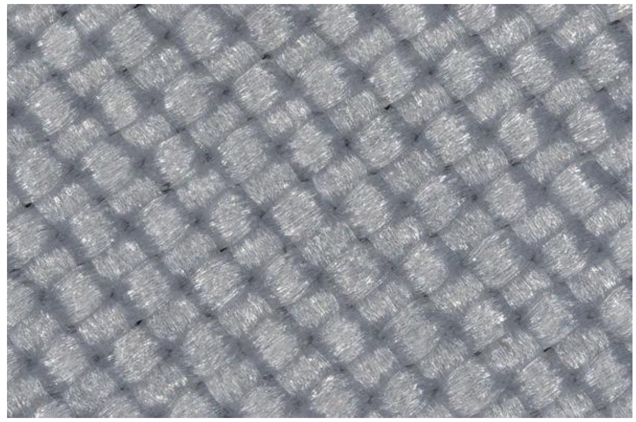

Figure 4. Calendared Teflon™ T-162 Fabric. *At 50x, weave appears tighter with closed interstices.*

A calendared version of the T-162 Teflon™ fabric was provided directly by the manufacturer and is shown in Figure 4. Visual inspection of the treated material indicates a noticeably tightened weave structure relative to the neat fabric, with reduced (approximately 90%) and less distinct interstices between yarns. This morphology is consistent with the effects of calendaring observed on Ortho Fabric.

The calendaring process parameters applied to the T-162 material were not disclosed to the ASM Team, as the manufacturer considers these details to be proprietary intellectual property. As a result, the evaluation conducted under this effort was limited to assessing the as-received material condition and its resultant performance characteristics, rather than the specific processing conditions used to achieve them.

Calendaring and subsequent testing were executed in two phases. The first phase applied calendaring parameters aligned with standard industry recommendations. The second phase implemented a targeted design of experiments (DOE) to optimize calendaring conditions. This DOE was conducted exclusively on Ortho Fabric due to its immediate availability in sufficient quantities for testing; expansion to additional fabric systems is planned in future work. The DOE examined the influence of calendaring temperature (200–230 °C), pressure (30–65 bar), and line speed (1.5–5 m/min). Primary response variables included pre- and post-tumbler tensile strength and elongation, supplemented by dust-related performance metrics for comparative evaluation.

IV. Testing Procedure

The ASM Team executed a subset of its Lunar Fabric Test Plan defined in ICES-2025-56 to characterize the baseline and post-exposure performance of the neat and calendared fabrics. Fabrics were received and processed in-house at NASA JSC's Advanced Materials Laboratory (AML), where they were sectioned into specimen geometries and quantities in accordance with the applicable ASTM test standards. Materials were conditioned by ASTM D1776 prior to testing. Baseline mechanical and physical properties were then established, including thickness (ASTM D1777), areal mass (ASTM D3776), air permeability (ASTM D737), stiffness (ASTM D4032), strip tensile strength and elongation (ASTM D5035), tongue tear resistance (ASTM D2261), and puncture resistance (ASTM F1342).

Abrasion resistance to lunar dust and rock has been identified as a primary driver of risk for lunar suit outer layer fabrics, making it a key discriminator in early material and post-processing down-selection. Following baseline characterization, fabrics were subjected to a NASA-developed rotary abrasion method (ASTM WK85994), which exposes the face side of six panels of fabric to continuous interaction with 1 pound of moving lunar simulant (CSM-LHT-1) in combination with 1 pound of ceramic tumbler media for 8 hours (Figure 5). Upon completion of the abrasion exposure, fabric panels were removed, sectioned into test specimens, and re-evaluated for strength and physical properties. Pre- and post-exposure results were compared to quantify performance degradation and identify durability trends.

In addition to mechanical degradation, the rotary abrasion test enables assessment of dust shedding and dust penetration behavior. Fabric mass was measured before exposure and again after post-test cleaning using a standardized brush and vacuum procedure. The change in mass provided a quantitative measure of simulant retention, offering insight into the fabric's ability to resist dust embedding and facilitate effective dust removal. Dust that penetrated completely through the fabric was also collected and weighed as part of the assessment.

Figure 5. Rotary Abrasion Tumbler. *(Left)Exterior of tumbler drum and roller base. (Center) Interior of drum showing lunar dust simulant and ceramic media. (Right top) A full panel of Ortho Fabric (Right bottom) Teflon™ T-162 fitted to a urethane coated nylon support frame.*

The calendared Teflon™ T-162 provided was not large enough to tumble the standard panel size of 13” x 7” so the specimen was trimmed to 5” x 5” and mounted in the center of a panel of urethane coated nylon (Figure 5). The urethane coating prevented dust from penetrating outside of the test specimen which would have obfuscated the results. Therefore, the quantity of dust that was collected was solely what penetrated through the Teflon™ test specimen.

Stern & Stern provided limited strength data for the neat and calendared Teflon™ for comparison which is provided in the following section. Therefore, the ASM team only collected air permeation and dust penetration data for this fabric.

V. Test Results

A. Ortho Fabric

Figure 6 reveals the effects of the 8-hour tumbler abrasion exposure on both the neat and Round 1 calendared Ortho Fabric. The neat Ortho (shown in the images on the left) and calendared Ortho (shown in the images on the right) exhibit clear differences in condition and surface characteristics across all points of inspection. The upper two images at 100x magnification show that prior to tumbling, the neat Ortho displays a more heterogeneous surface, with clearly defined yarn bundles and visible interstices between yarns. In contrast, the calendared Ortho presents a more uniform appearance, with flattened yarn surfaces and reduced pore definition, indicating a tighter and more consolidated weave resulting from the calendaring process.

Following tumbling and vacuum cleaning, these differences became more pronounced at the panel level (center images). The neat Ortho panels appeared slightly darker and more mottled, consistent with increased surface

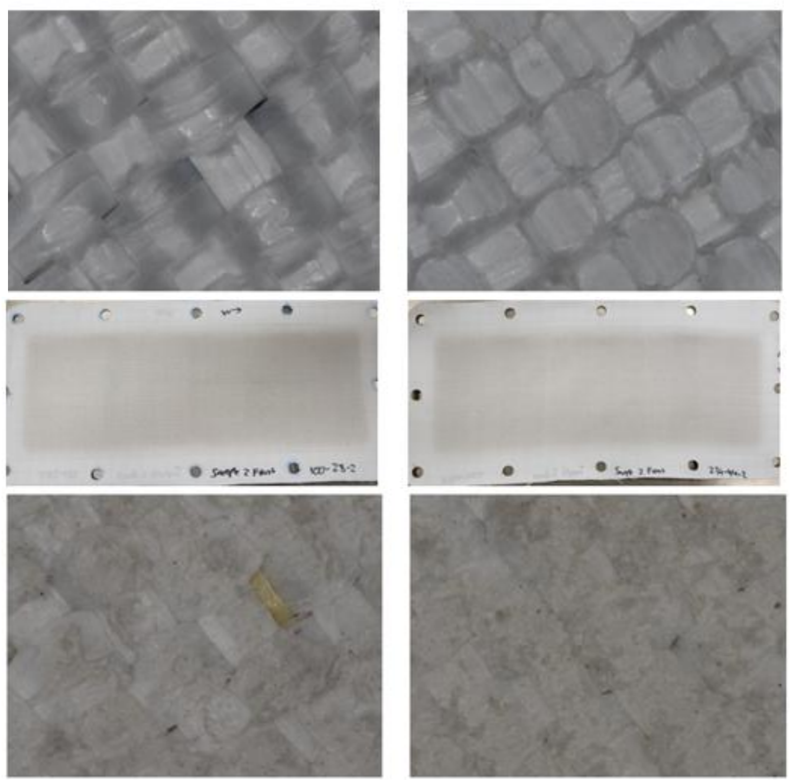

Figure 6. Ortho Fabric Tumbler Results. *(Top Left) 100x Neat Ortho (Top Right) 100x Calendared Ortho (Center Left) Neat Ortho panel post tumbler and cleaning (Center Right) Calendared Ortho panel post tumbler and cleaning (Bottom Left) 100x Post tumbler neat Ortho (Bottom Right) 100x Post tumbler calendared Ortho.*

roughness and a greater tendency to retain dust or debris within the weave. The calendared Ortho panels maintained a lighter, more uniform appearance, suggesting reduced dust entrapment and improved cleanability due to the smoother, densified surface.

Post-tumble images taken at 100x magnification (bottom) further highlight differences in weave stability and damage. The Neat Ortho fabric shows localized yarn displacement, increased visibility of inter-yarn gaps, and minor fibrillation at yarn crossover points, indicating greater susceptibility to mechanical disturbance during tumbling. By comparison, the calendared Ortho retains tighter yarn packing with minimal change from its pre-tumble condition. The yarn crossovers remain intact, surface fibrillation is limited, and overall weave definition is preserved. Collectively, these observations indicate that calendaring improves weave tightness, surface uniformity, and resistance to abrasion-induced damage relative to the baseline Ortho condition.

Table 2 summarizes the mechanical property data collected on both neat and calendared Ortho Fabric pre tumbler abrasion testing. Also listed for reference are the Lunar Fabric requirements set by the ASM team as detailed in ICES-2025-56. The pre-tumbler data show that calendaring produces a densification of the Ortho fabric that strongly affects air flow, stiffness (hand), and certain mechanical properties, while leaving others largely unchanged. Thickness is reduced by approximately 28%, dropping from 0.024 in (0.609 mm) to 0.017 in (0.613 mm), which is consistent with yarn flattening and consolidation of the weave. Areal mass remains effectively unchanged (-0.7%), indicating that the process redistributes material rather than removing it. This confirms that calendaring is primarily a geometric modification rather than a mass-altering one.

Table 2: Neat and Calendared Ortho Pre Tumbler Test Data (Avg Values)

	Neat Ortho	Calendared Ortho	% Change	Threshold Value	Goal Value
Thickness (in)	0.024	0.017	-28%	<0.03	<0.02
Areal mass (oz/yd^2)	14.5	14.4	-0.7%	<18.5	<14.8
Air Permeability (cfm@125 Pa)	22.5	3.7	-84%	<1	<0
Cantilever Stiffness (µNm)	297	235	-21%	-	-
Strip Tensile (lbf/in)	395*	403	+2%	>200	>400
Elongation (%)	34*	35	+3%	>4	>8
Tongue Tear (lbf)	229	230	+0.4%	>70	>100
Puncture (ozf)	38.8	32.8	-15%	>72	>215

**Values represent averages obtained during this effort, with neat and calendared Ortho tested concurrently. Previously reported neat Ortho tensile strength (507 lbf/in) and elongation (59%) from ICES-2025-56 differ from the values presented here. The source of this discrepancy is under investigation. Initial hypotheses include increased measurement variability associated with the dual-layer construction of Ortho Fabric, which may affect load distribution and test repeatability, as well as potential operator-dependent influences. Further evaluation is ongoing to quantify these effects in terms of test precision and reproducibility.*

Air permeability is the most dramatically affected parameter, decreasing by roughly 84% from 22.5 to 3.7 cfm @125 Pa. This reduction aligns with the observed tightening of interstices and reduced pore size seen microscopically and suggests a significantly improved barrier to particulate ingress. While the calendared fabric does not meet the most aggressive threshold or goal values for air permeability, the magnitude of improvement demonstrates that calendaring is an effective lever for reducing bulk flow paths without introducing coatings or laminates.

Mechanical properties show mixed but generally acceptable impacts. Single cantilever stiffness decreases by about 21%, indicating a softer hand and increased drape, which may be beneficial for garment mobility. Strip tensile strength in the warp direction increases slightly by approximately 2%; however, this change falls within the expected test variability and is not considered statistically significant. Similarly, elongation shows a modest increase (~3%), which is also within the range of measurement variability. The data suggests that calendaring does not constrain yarn mobility and does not embrittle the fabric.

Damage-tolerant properties are largely preserved. Tongue tear strength is effectively unchanged (+0.4%), indicating that calendaring does not meaningfully degrade tear propagation resistance. Puncture resistance decreases by approximately 15%; however, given that baseline (neat) performance is already below the threshold requirement, this reduction is not considered the primary limiting factor, and puncture performance will need to be improved through alternative material or system-level design strategies. Overall, the data indicates that calendaring provides substantial gains in surface consolidation and air permeability reduction with manageable trade-offs in thickness, stiffness, and puncture performance, and without compromising critical structural integrity metrics.

Table 3 summarizes the mechanical property data collected on both neat and calendared Ortho Fabric post tumbler abrasion testing. Also listed for reference are the Lunar Fabric requirements set by the ASM team as detailed in ICES-2025-56.

The post-tumbler results on Ortho show that the effects of calendaring remain clear after mechanical dust exposure, with the most significant benefit continuing to be the reduction in air permeability. After tumbling, air permeability of the calendared Ortho is reduced by approximately 91% relative to the neat fabric (1.1 vs. 12.7 cfm@125 Pa), indicating that the calendared structure retains its tightened interstices and does not reopen under abrasion. This result is encouraging given the aggressive nature of the tumbling process and supports the conclusion that calendaring provides a durable improvement in barrier performance rather than a superficial surface effect.

Thickness and areal mass remain relatively stable post-tumble, with only minor changes observed. Thickness shows a slight increase (+1%) in the calendared condition, likely attributable to elastic recovery or localized yarn relaxation following tumbling, while areal mass decreases modestly (-3%), consistent with minor surface fiber loss. These changes are small and remain well within threshold and goal limits, indicating no meaningful structural degradation due to calendaring under dust abrasion.

Table 3: Neat and Calendared Ortho Post Tumbler Test Data

	Neat Ortho	Calendared Ortho	% Change		Threshold Value	Goal Value
Thickness (in)	0.020	0.021	+1%		<0.03	<0.02
Areal mass (oz/yd^2)	15.5	15.1	-3%		<18.5	<14.8
Air Permeability (cfm@125 Pa)	12.7	1.1	-91%		<1	<0
Cantilever Stiffness (µNm)	267	411	+54%		-	-
Strip Tensile (lbf/in)	297*	260	-12%		>200	>400
Elongation (%)	15*	17	+13%		>4	>8
Tongue Tear (lbf)	120	86	-28%		>70	>100
Puncture (ozf)	84.8	63.2	-25%		>72	>215
Simulant Penetrated (g/m^2)	109	2	-98%		<0.1	25 clean
Simulant Adhesion (g/m^2)	341	277	-19%		<6.5	<2.5
Simulant Uptake (g/m^2)	19	15	-21%		<1.0	<0.1

**Values represent averages obtained during this effort, with neat and calendared Ortho post tumbler tested concurrently. Previously reported neat Ortho tensile strength (302 lbf/in) and elongation (25%) from ICES-2025-56 differ from the values presented here. The source of this discrepancy is under investigation. Initial hypotheses include increased measurement variability associated with the dual-layer construction of Ortho Fabric, which may affect load distribution and test repeatability, as well as potential operator-dependent influences. Further evaluation is ongoing to quantify these effects in terms of test precision and reproducibility.*

Changes in mechanical properties after tumbling highlight a shift in fabric hand and loading response. Cantilever stiffness increases substantially in the calendared fabric (+54%), suggesting that post-tumble compaction, surface glazing, or dust-induced yarn locking may stiffen the structure relative to the neat condition. Strip tensile strength decreases by approximately 12%, but the calendared fabric continues to exceed the minimum threshold requirement (>200 lbf), though it no longer meets the goal value. Elongation is increased by roughly 13%, remaining above the minimum requirement and further confirming yarn mobility is not negatively impacted in the consolidated weave.

Other properties show some degradation but remain acceptable relative to requirements. Tongue tear strength decreases by about 28% in the calendared fabric yet stays above the threshold value, indicating that tear resistance is reduced but not unacceptably compromised. Overall puncture resistance is improved by dust exposure but drops by approximately 25% between the neat and calendared versions, suggesting calendaring slightly reduces compliance under concentrated loading, which will need to be addressed through alternative material or system-level design strategies.

The dust-related metrics in the final three rows further reinforce the effectiveness of calendaring in improving dust performance. Simulant penetration shows the most pronounced improvement, decreasing by approximately 99% in the calendared Ortho (2 g/m² versus 165 g/m² for the neat fabric). This dramatic reduction indicates that calendaring is highly effective at closing inter-yarn pathways that enable bulk dust transport, bringing the material well below the threshold requirement and very near the stated cleanliness goal. This result directly supports the role of calendaring as a primary dust-mitigation mechanism for lunar fabric applications.

Simulant adhesion decreases modestly by about 2% in the calendared condition (277 g/m² versus 284 g/m²). While the absolute reduction is small, it suggests that the smoother, flattened yarn surfaces produced by calendaring may slightly reduce mechanical interlocking of particles at the surface. Importantly, both neat and calendared fabrics remain well above the threshold and goal values, indicating that calendaring alone is not sufficient to address adhesion-driven dust fouling and that additional surface treatments or coatings would be required to meaningfully reduce dust cling.

Simulant caking is reduced by approximately 21% in the calendared fabric (15 g/m² versus 19 g/m²), consistent with the observed reduction in surface roughness providing fewer places to trap and compact dust during tumbling. The calendared Ortho meets the threshold requirement and approaches the goal value, indicating a meaningful improvement in resistance to dust buildup without introducing additional coatings. Collectively, these dust-specific results show that calendaring delivers a step-change improvement in dust penetration resistance and modest benefits in adhesion and caking behavior, while leaving room for complementary surface modifications to further improve dust release performance.

One observation made when viewing the backside of the fabric was that the Kevlar® ripstop grid was noticeably smaller on the calendared version of the fabric. Measurements verified that neat Ortho has a grid that is 9.26 x 9.00 mm while the calendared version measured 8.93 x 8.81 mm. This ~3.4% decrease in length of the Kevlar® grid implies the calendaring process tightened the yarns and caused some minimal shrinkage of the fabric.

B. Teflon™ T-162

Figure 7 demonstrates the effects of the 8-hour tumbler abrasion exposure on both the neat and calendared Teflon™ T-162 Fabric. Mirroring Ortho Fabric, the neat Teflon™ (shown in the images on the left) and calendared Teflon™ (shown in the images on the right) behaved in a similar manner. The upper two images at 100x magnification show that prior to tumbling, the neat Teflon™ weave is open with visible interstices between yarns. The calendared version is closer and also has flattened yarn bundles.

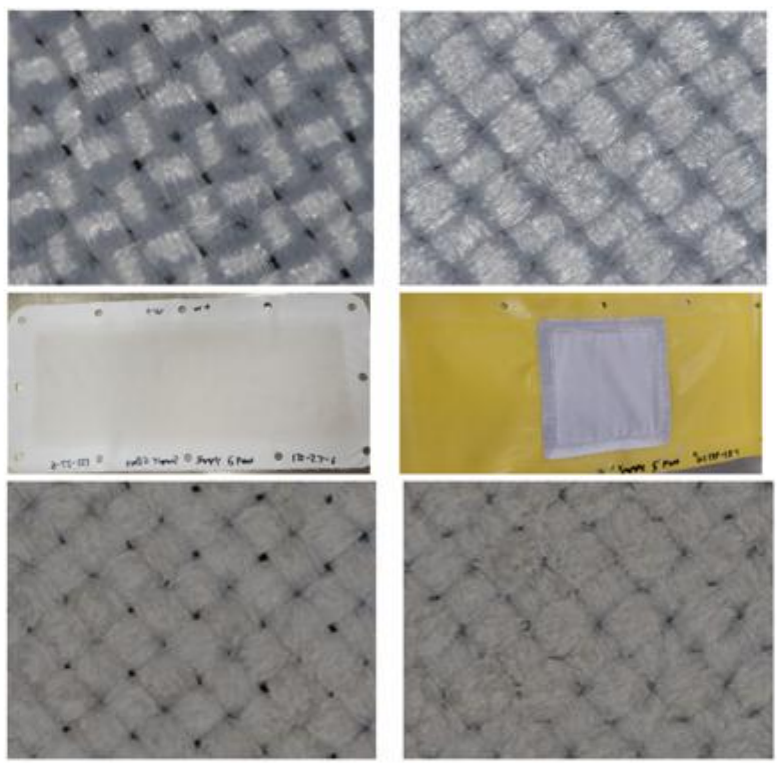

Figure 7. Teflon™ T-162 Tumbler Results. *(Top Left) 100x Neat Teflon™ (Top Right) 100x Calendared Teflon™ (Center Left) Neat Teflon™ panel post tumbler and cleaning (Center Right) Calendared Teflon™ panel post tumbler and cleaning (Bottom Left) 100x Post tumbler neat Teflon™ (Bottom Right) 100x Post tumbler calendared Teflon™.*

The difference in tumbled panels is a little less obvious than the Ortho counterpart mainly because the calendared Teflon™ samples were small and are mounted on the urethane nylon support panel, so the white balances are different causing the calendared sample to appear darker. However, post tumbler microscopy reveals that the coloring is nearly identical and that the tightened structure from calendaring remained after tumbling.

Table 4 summarizes the pre-tumbler results for Teflon™ T-162. Data reveals that calendaring produces trends consistent with those observed for Ortho Fabric, particularly in terms of surface consolidation and air permeability reduction. Air permeability decreased by approximately 84%, closely mirroring the magnitude of reduction seen in calendared Ortho, confirming that calendaring is an effective and repeatable method for tightening inter-yarn pathways across different fabric constructions. Thickness remains unchanged and areal mass increases only slightly, indicating that, as with Ortho, calendaring primarily redistributes yarn geometry rather than fundamentally altering the fabric structure.

Mechanical impacts are minimal and less pronounced than those observed for Ortho Fabric. Cantilever stiffness is unchanged, strip tensile strength shows only a small decrease, and elongation increases, suggesting that T-162 is more mechanically tolerant of the calendaring process.

Table 4: Neat and Calendared Teflon™ T-162 Pre Tumbler Test Data

	Neat Teflon	Calendared Teflon	% Change		Threshold Value	Goal Value
Thickness (in)	0.008	0.008	0%		<0.03	<0.02
Areal mass (oz/yd^2)	9.3	9.8	+5%		<18.5	<14.8
Air Permeability (cfm@125 Pa)	13.9	2.2	-84%		<1	<0
Cantilever Stiffness (µNm)	17	17	0%		-	-
Strip Tensile (lbf/in)	78	74	-5%		>200	>400
Elongation (%)	74	89	+20%		>4	>8
Tongue Tear (lbf)	-	-	-		>70	>100
Puncture (ozf)	-	-	-		>72	>215

In contrast to Ortho, T-162 retained its baseline mechanical behavior while still achieving significant gains in permeability reduction. Note that tear and puncture resistance were not evaluated because of the smaller specimen size provided for the T-162 assessment.

Table 5 summarizes the mechanical property data collected on both neat and calendared Teflon™ T-162 fabric post tumbler abrasion testing. Also listed for reference are the Lunar Fabric requirements set by the ASM team as detailed in ICES-2025-56.

Table 5: Neat and Calendared Teflon™ Post Tumbler Test Data

	Neat Teflon	Calendared Teflon	% Change		Threshold Value	Goal Value
Thickness (in)	0.0095	0.0104	+9%		<0.03	<0.02
Areal mass (oz/yd^2)	9.9	10.1	+2%		<18.5	<14.8
Air Permeability (cfm@125 Pa)	5.0	7.8	+56%		<1	<0
Cantilever Stiffness (µNm)	14	17	+21%		-	-
Strip Tensile (lbf/in)	-	-	-		>200	>400
Elongation (%)	-	-	-		>4	>8
Tongue Tear (lbf)	-	-	-		>70	>100
Puncture (ozf)	-	-	-		>72	>215
Simulant Penetrated (g/m^2)	96.7	0.4	-99.6%		<0.1	25 clean
Simulant Adhesion (g/m^2)	319	-	-		<6.5	<2.5
Simulant Uptake (g/m^2)	20	-	-		<1.0	<0.1

When compared to the Ortho Fabric post-tumbler results, the calendared Teflon™ T-162 data show several consistent structural trends alongside one notable divergence in transport behavior. Similar to Ortho, the thickness increases and areal mass remains roughly the same after tumbling. The thickness increase (+9%) and modest areal mass gain (+2%) are consistent with elastic recovery and the incorporation of residual dust within the fabric structure following abrasion. This behavior mirrors the Ortho response and suggests that post-tumbler bulk changes are driven more by mechanical agitation and dust interaction than by fabric construction alone.

Cantilever stiffness also increases after tumbling (+21%), consistent with the Ortho results. This stiffening is likely attributable to surface glazing, yarn flattening, and dust-induced inter-yarn locking, which reduce compliance after abrasion exposure. The similarity in stiffness response between T-162 and Ortho indicates that post-tumbler stiffening is a general consequence of calendaring followed by dust exposure, rather than a material-specific anomaly.

The most confounding result relative to Ortho is the increase in air permeability (+56%) observed for calendared T-162, which contrasts with the strong reductions measured for calendared Ortho post-tumbler. Despite this increase in bulk air flow, simulant penetration is reduced by 99.7%, dropping from 123 g/m² to 0.4 g/m². This apparent contradiction suggests that air permeability and dust penetration are decoupled for T-162. Unlike Ortho, which relies on yarn packing to restrict both air and particle transport, T-162 likely benefits from thermoplastic behavior during calendaring, where localized polymer flow, surface smoothing, or partial pore sealing inhibits particle ingress without uniformly reducing interconnected flow paths measured in air permeability testing.

This behavior highlights a key material distinction: for Ortho Fabric, calendaring primarily improves dust resistance by mechanically tightening the weave, directly reducing air permeability. For Teflon™ T-162, calendaring appears to modify surface and near-surface features that block particulate penetration while leaving or even increasing macro-scale air pathways. As a result, dust penetration is not well predicted by air permeability for T-162, whereas the two metrics are more closely coupled for Ortho. Collectively, these results underscore the need to evaluate dust transport and air permeability independently when comparing fiber systems, and they demonstrate that calendaring can be highly effective at reducing dust penetration in T-162 even when traditional permeability metrics move in an unfavorable direction.

Overall, the results reinforce conclusions from the Ortho Fabric testing: calendaring reliably improves barrier performance with fabric-specific mechanical responses, and T-162 appears particularly well suited to the process with negligible mechanical penalty.

C. Optimization of Calendaring Paraments

After observing that Ortho Fabric's post tumbler tensile strength dropped from 297 lbs. to 260 lbs. (-12% change) in Round 1 calendaring performed at 215°C, 50 bar, and 1.5 m/min, the influence of calendaring parameters was further investigated in a design of experiment (DOE). Individual Ortho Fabric panels were again calendared at NCSU using systematically varied machine settings. Half of the panels were reserved for baseline tensile and elongation measurements, while the remaining panels were subjected to the same 8-hour rotary tumbler exposure used in prior testing. Each panel was then subdivided into five equal tensile specimens and tested in the JSC AML. The resulting data are summarized in Table 6.

Table 6: Effects on Tensile Strength and Elongation of Calendaring Ortho Fabric at Varying Parameters Pre and Post Tumbler

Panel	Temp/Press/Speed	Pre Tumbler Tensile (lbf)	Post Tumbler Tensile (lbf)	% Change	Pre Tumbler Elong	Post Tumbler Elong	% Change
ROUND 1							
Uncalendared Ortho	-	395	297	-25%	34	15	-56%
Calendared Ortho	215 / 50 / 1.5	403	260	-35%	35	17	-51%
ROUND 2 DOE							
1	200 / 35 / 1.5	386	282	-27%	36	16	-56%
2	200 / 35 / 5	402	283	-30%	37	14	-62%
3	200 / 65 / 1.5	400	287	-28%	37	18	-51%
4	200 / 65 / 5	400	282	-30%	37	16	-57%
5	230 / 35 /1.5	386	278	-28%	37	18	-51%
6	230 / 35 / 5	400	275	-31%	39	19	-51%
7	230 / 65 / 1.5	407	282	-31%	38	16	-58%
8	230 / 65 / 5	397	288	-27%	38	15	-61%
9	210 / 30 / 1.5 2-pass	411	285	-31%	40	16	-60%
10	210 / 30 / 5 2-pass	402	268	-33%	39	15	-62%
11	215 / 50 / 3.5	400	290	-28%	39	15	-62%

The DOE results show that calendaring parameters influence both the magnitude of tensile and elongation loss and the absolute post-tumbler performance, although the overall response range is relatively narrow. When examining the pre-tumbler tensile strength, Panel 7 and Panel 9 lost less tensile strength than the Round 1 calendaring by a narrow margin. Panel 7 had a high temperature (230C), high pressure (65 bar), and low speed (1.5 m/min). Panel 9 had a medium temperature (210C), low pressure (30 bar), low speed (1.5 m/min), and was run through the machine twice.

All other panels lost a similar amount or more. Interestingly, Panels 1 and 5 lost the most (-24%) even though they were calendared at both temperature extremes.

In addition to confirming that calendaring parameters influence tensile and elongation losses, the DOE provides insight into how temperature, pressure, and speed interact to affect pre-tumbler tensile strength retention. Across the matrix, higher calendaring temperatures tend to correlate with slightly greater reductions in pre-tumbler tensile strength, particularly when combined with lower pressure. Panels processed at 230 °C generally show lower pre-tumbler tensile values than those calendared at 200–210 °C, suggesting that elevated temperature promotes increased yarn flattening or micro-damage prior to dust exposure. However, this effect can be partially mitigated by higher pressure, as evidenced by Panel 7, where high temperature and high pressure together resulted in tensile losses comparable to lower-temperature cases.

Pressure appears to play a role relative to temperature. Higher pressures (65 bar) tend to preserve tensile strength more effectively at a given temperature by promoting uniform yarn consolidation rather than localized deformation. Conversely, lower pressures (30–35 bar) at moderate to high temperatures generally result in slightly greater tensile losses, unless offset by reduced speed or additional passes. Speed effects are comparatively subtle within the tested range; lower speeds (1.5 m/min) are associated with marginally better tensile retention, likely due to more uniform heat and pressure transfer, while higher speeds (5 m/min) show slightly increased variability but no step-change degradation.

Pre-elongation results show a narrower spread than tensile strength and are relatively insensitive to individual parameter changes. Across all DOE conditions, pre-elongation remains clustered between approximately 36–40%, indicating that calendaring consistently constrains yarn mobility regardless of parameter combination. While higher temperatures tend to produce slightly lower pre-elongation values, the differences are modest and do not scale strongly with pressure or speed. This suggests that elongation reduction is primarily driven by the act of calendaring itself rather than fine-tuning of process parameters. Overall, the DOE indicates that temperature is the dominant driver for tensile strength sensitivity, pressure can mitigate temperature effects, and speed plays a secondary role, while pre-elongation is comparatively stable across the parameter space.

The post-tumbler tensile and elongation results indicate that, regardless of calendaring parameter selection, dust abrasion and mechanical agitation dominate the degradation response once the fabric is exposed to the rotary tumbler environment. Across all DOE conditions, post-tumbler tensile strength converges into a relatively narrow band (approximately 268–290 lbf), and post-tumbler elongation similarly clusters between roughly 14–19%. This convergence suggests that while calendaring parameters influence pre-tumbler properties, their influence on post-tumbler performance is secondary to the effects of dust exposure and abrasion.

Temperature, pressure, and speed do not produce a strong trend in post-tumbler tensile strength or elongation. Parameter sets that performed well pre-tumble do not necessarily translate into meaningfully higher post-tumble properties, indicating that the tumbling process effectively "resets" the mechanical response by driving the fabric toward a common damage state. Panels processed at higher temperatures or pressures do not show a systematic advantage in post-tumbler retention, reinforcing the conclusion that calendaring parameter optimization alone cannot eliminate the mechanical penalties associated with dust abrasion.

Importantly, although percent losses vary, absolute post-tumbler tensile and elongation values remain above minimum threshold requirements for all DOE conditions. This suggests that calendaring, even under more aggressive settings, does not introduce a catastrophic failure mode when followed by dust exposure. Instead, calendaring establishes the initial fabric condition, while post-tumbler performance appears governed by inherent yarn and weave damage mechanisms under abrasive loading. These results support focusing calendaring optimization on improving barrier performance and minimizing *pre-tumbler* degradation, while addressing post-tumbler mechanical retention through complementary design features such as coatings, yarn selection, or weave architecture rather than further adjustment of calendaring parameters alone.

Table 7 reinforces the conclusions drawn from the tensile and elongation DOE by showing that dust-related performance is far more sensitive to calendaring than post-tumbler mechanical strength, and that meaningful separation between parameter sets does exist for simulant metrics even when tensile results converge.

Table 7: Effects on Simulant Metrics of Calendared Ortho Fabric at Varying Parameters

Panel	Temp/Press/Speed	Simulant Penetrated	Simulant Adhesion	Simulant Uptake	Simulant Removed
Neat	-	86.8	397	15	45
1	200 / 35 / 1.5	0.3	306	13	18
2	200 / 35 / 5	12.2	403	13	28
3	200 / 65 / 1.5	0.1	310	15	9
4	200 / 65 / 5	8.2	366	13	15
5	230 / 35 /1.5	1.3	421	14	24
6	230 / 35 / 5	0.9	373	16	3
7	230 / 65 / 1.5	0.7	290	13	16
8	230 / 65 / 5	1.1	399	14	26
9	210 / 30 / 1.5 2-pass	2.2	372	15	22
10	210 / 30 / 5 2-pass	9.4	426	16	16
11	215 / 50 / 3.5	2.1	382	15	33

First, simulant penetration shows a dramatic reduction for all calendared conditions relative to the neat control, confirming that calendaring is the dominant mechanism driving dust exclusion. Across the DOE space, penetration values drop from 86.8 g/m² (neat) to ≤12.2 g/m², with most parameter sets achieving ≤2 g/m². Unlike post-tumbler tensile strength, penetration remains sensitive to processing conditions. Lower penetration generally correlates with increased fabric consolidation, achieved either through higher temperature, higher pressure, or increased dwell (e.g., double-pass processing). Panels 1, 5, 6, and 7 demonstrate that multiple parameter combinations can yield similarly low penetration, reinforcing the earlier observation that temperature and pressure can compensate for one another.

Simulant adhesion, by contrast, shows relatively weak dependence on calendaring parameters and remains high across all conditions (≈290–426 g/m²). This mirrors earlier observations that calendaring alone does not substantially alter surface chemistry or electrostatic behavior and therefore has limited influence on dust adhesion. Variability in adhesion appears to be not strongly correlated with temperature, pressure, or speed, supporting the conclusion that adhesion is not a primary discriminant for calendaring optimization and would need to be addressed through coatings or surface treatments. Simulant uptake remains tightly clustered (≈13–16 g/m²) across all panels, indicating that once dust enters the surface layer, the total mass retained within the fabric thickness is relatively insensitive to calendaring parameter variations.

Finally, simulant removed from the fabric by vacuuming shows moderate variability and appears loosely correlated with adhesion rather than penetration. Panels with lower adhesion generally exhibit lower removal mass, suggesting that smoother or more consolidated surfaces may limit both dust attachment and subsequent release. However, no single parameter set clearly optimizes removal alone, reinforcing that calendaring primarily controls ingress, not dust release.

VI. Conclusion

To enhance dust-blocking performance for lunar surface applications, the Artemis Suit Materials Team investigated calendaring as a continuous roll-to-roll mechanical finishing process capable of compressing and flattening woven fabrics. By applying controlled heat and pressure, calendaring reduces effective pore size and modifies surface texture without fundamentally altering fabric mass or architecture, making it an attractive preprocessing step for EPG materials.

Round 1 testing demonstrated that calendaring provides a substantial improvement in dust mitigation for both Ortho Fabric and Teflon™ T-162. For Ortho Fabric, calendaring resulted in large reductions in air permeability and simulant penetration, confirming effective closure of inter-yarn pathways. However, these gains were accompanied by measurable reductions in tensile strength and elongation, particularly after rotary tumbler exposure, indicating increased sensitivity of the aramid-based construction to thermo-mechanical processing. In contrast, T-162 exhibited minimal mechanical degradation while achieving a 99.7% reduction in dust penetration, despite an unexpected increase in air permeability post-tumble. This decoupling of air permeability and dust ingress highlights a material-dependent response to calendaring and underscores the importance of evaluating particulate transport independently from bulk flow metrics.

Round 2 testing focused on optimizing calendaring parameters for Ortho Fabric through a structured design of experiments. The DOE showed that temperature is the dominant driver of tensile and elongation loss, with higher temperatures generally reducing pre-tumbler mechanical properties. Pressure was found to partially mitigate temperature effects, while line speed played a secondary role within the tested range. Importantly, post-tumbler tensile strength and elongation converged across all parameter sets, indicating that dust abrasion dominates mechanical degradation once exposure occurs. In contrast, dust penetration remained highly sensitive to calendaring conditions, providing a clear discriminator between parameter sets and reinforcing the value of calendaring for dust exclusion rather than post-abrasion mechanical retention.

Based on these findings, calendaring at moderate temperature, elevated pressure, and low line speed provides the best balance for Ortho Fabric, minimizing pre-tumbler mechanical penalties while achieving robust and durable reductions in dust penetration. For PTFE-based fabrics such as T-162, calendaring is expected to be mechanically benign and highly effective at blocking particulate ingress, even when traditional air permeability metrics suggest limited consolidation. Overall, calendaring is validated as a viable and scalable preprocessing technique for lunar suit fabrics, with material-specific responses that should be considered when tailoring processing parameters across different fiber systems.

Future work will expand the calendaring trade space beyond Ortho Fabric to include Teflon-based systems as well as additional candidate materials such as Kevlar®, Vectran®, and PBO. A similar DOE approach will be applied to these materials to evaluate the influence of calendaring parameters on mechanical performance, permeability, and dust resistance. In particular, additional testing will investigate the relationship between air permeability and dust resistance, as these properties appeared strongly coupled in Ortho Fabric but not in Teflon-based systems. Understanding whether this behavior is driven by material composition, weave architecture, or surface energy effects will be critical to informing material selection and process optimization.

Electrostatic effects were not considered within the scope of this effort, as all testing was conducted under ambient laboratory conditions with nominal humidity. Given the known sensitivity of lunar dust behavior to electrostatic charging in vacuum environments, future testing should incorporate vacuum conditions and charged simulant to better represent lunar surface interactions. Additionally, further evaluation is required to assess the long-term implications of calendaring on suit durability, including performance under thermal cycling, repeated flexing, and abrasive exposure. Considerations related to manufacturability such as seam construction, seam sealing, and integration into garment assemblies will also be necessary to ensure that calendared materials can be effectively implemented within a flight-ready Environmental Protection Garment system.

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