Artemis Suit Material Effects of Calendaring Woven Fabrics on Dust Resistance

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DATE

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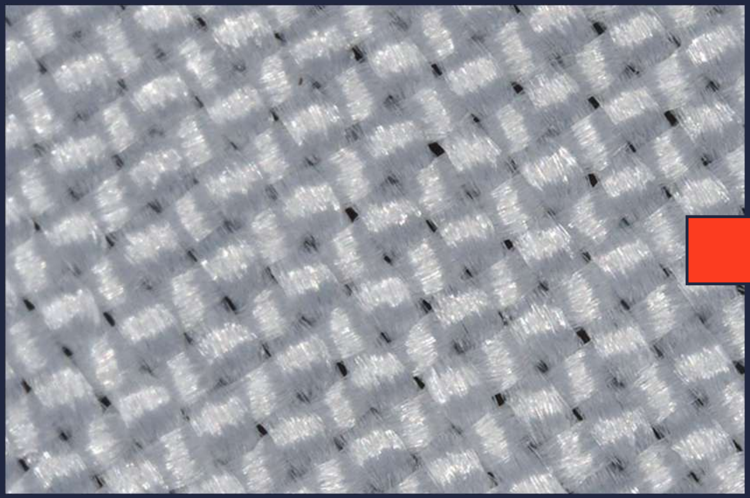
Artificial Intelligence (AI) Usage Disclosure: This document was created with assistance from Microsoft Co-pilot for editing and interpreting results. The content has been reviewed and edited by Robert Jones. More information on the extent and nature of AI usage is included in the Methods or Acknowledgements sections of the document.

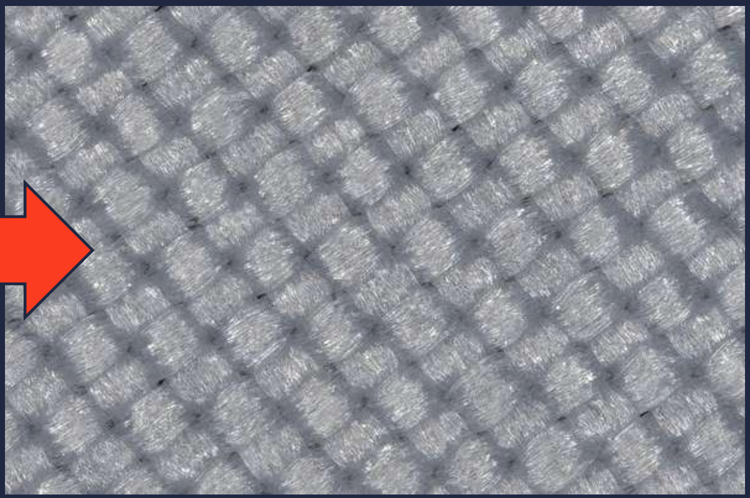
Project Background and Scope

- *Artemis Suit Material Overview* presented in ICES-2025-56
  - Technology infusion project to design, fabricate and test new outer shell fabrics for lunar EVA suits

Uncalendared Teflon



Calendared Teflon

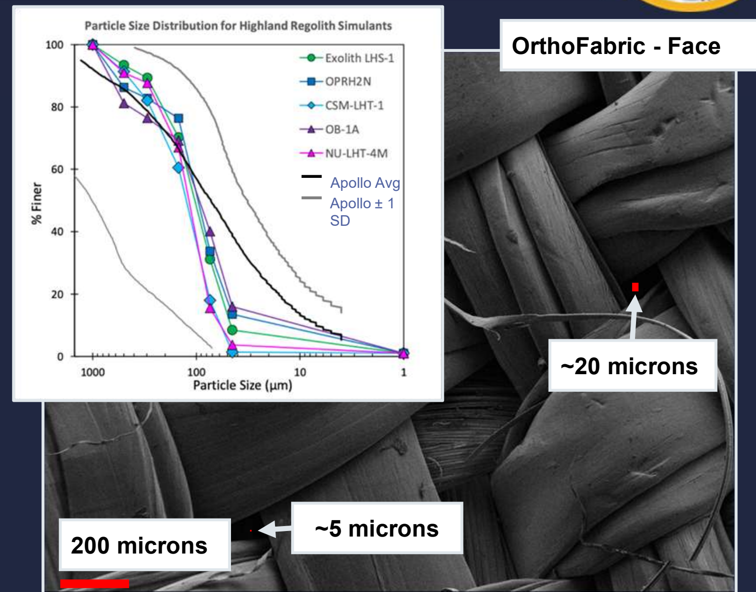


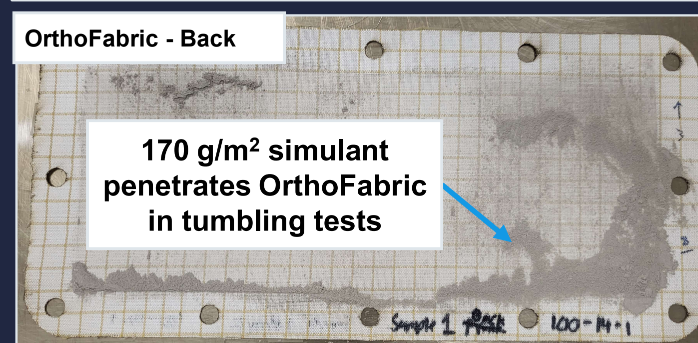
- BLUF: Calendaring may be a low-cost, scalable method to dramatically reduce lunar dust penetration of certain fabrics.

Lunar Dust Challenge

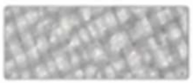
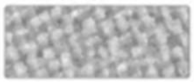
- Why does this matter?
  - Lunar dust is abrasive
  - Penetrates most woven structures
  - Threatens environmental protection garment (EPG) durability and astronaut safety
- Ortho Fabric 116 has poor dust resistance
  - 170 g/m^2 dust penetration in tumbling
  - MLI degradation; bladder/restraint hazards
  - Thermal burden-changes optical properties
  - Excess carried into HLS which puts ECLSS at risk

Takeaway: Dust ingress remains a major driver for outer shell material development



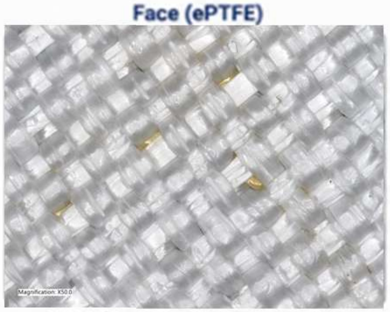


Fabrics Evaluated

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

Ortho Fabric Structure (20x Magnification)

Face (ePTFE)



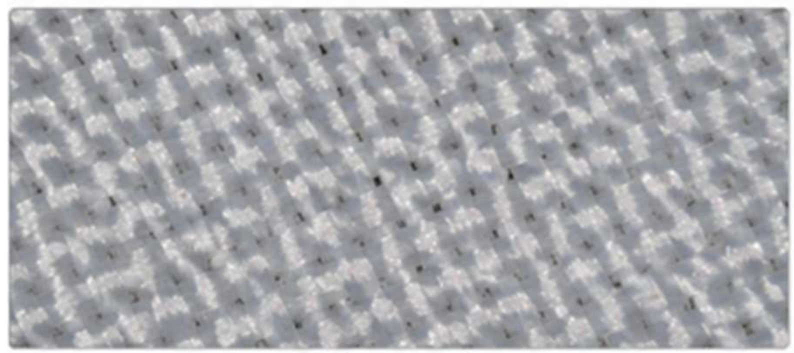
ePTFE (Gore-Tex®) yarns are white.

Back (Nomex / Kevlar Ripstop)

Nomex® yarns are white and Kevlar® ripstop yarns are gold.

- 2-layer basket weave construction
- Face: Expanded PTFE (Gore-Tex®) yarns
- Back: Nomex® with Kevlar® ripstop
- Used on most of the EMU suit (torso, arms, legs, boots, gloves, etc.)

Teflon™ T-162 Fabric Structure (20x Magnification)



PTFE yarns are white.

- Single-layer plain weave construction
- PTFE (Teflon™) yarns
- Used on glove backs and gauntlets (Phase VI EMU) and in select locations on Apollo suits

Both Ortho 116 and Teflon™ T-162 are legacy fabrics on the EMU and highly relevant to lunar suit development

Test Approach

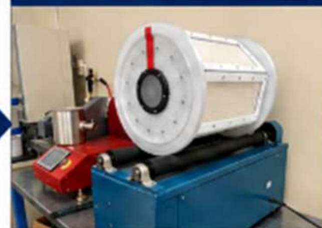
1. BASELINE CHARACTERIZATION

Neat (uncalendared) fabric samples characterized prior to calendaring.

2. CALENDARING PROCESS

Fabrics passed through heated rollers under pressure to compress and reduce pore size.

3. 8-HOUR ROTARY TUMBLER EXPOSURE



Samples tumbled with lunar dust simulant for 8 hours to evaluate dust interaction and penetration.

4. POST-EXPOSURE CONDITIONING

Samples cleaned of surface dust and conditioned prior to testing.

5. POST-EXPOSURE TESTING

Mechanical, barrier, and dust performance tests conducted and compared to baseline.

8-HOUR ROTARY TUMBLER

- Conforms to ASTM WK85994
- 8 hours
- CSM-LHT-1 Lunar Dust Simulant and ceramic tumbler media
- 3D Printed drum w/ 6 fabric panels

TESTS PERFORMED

- Thickness / Mass
- Air Permeability
- Cantilever Stiffness
- Strip Tensile
- Elongation
- Tongue Tear
- Puncture

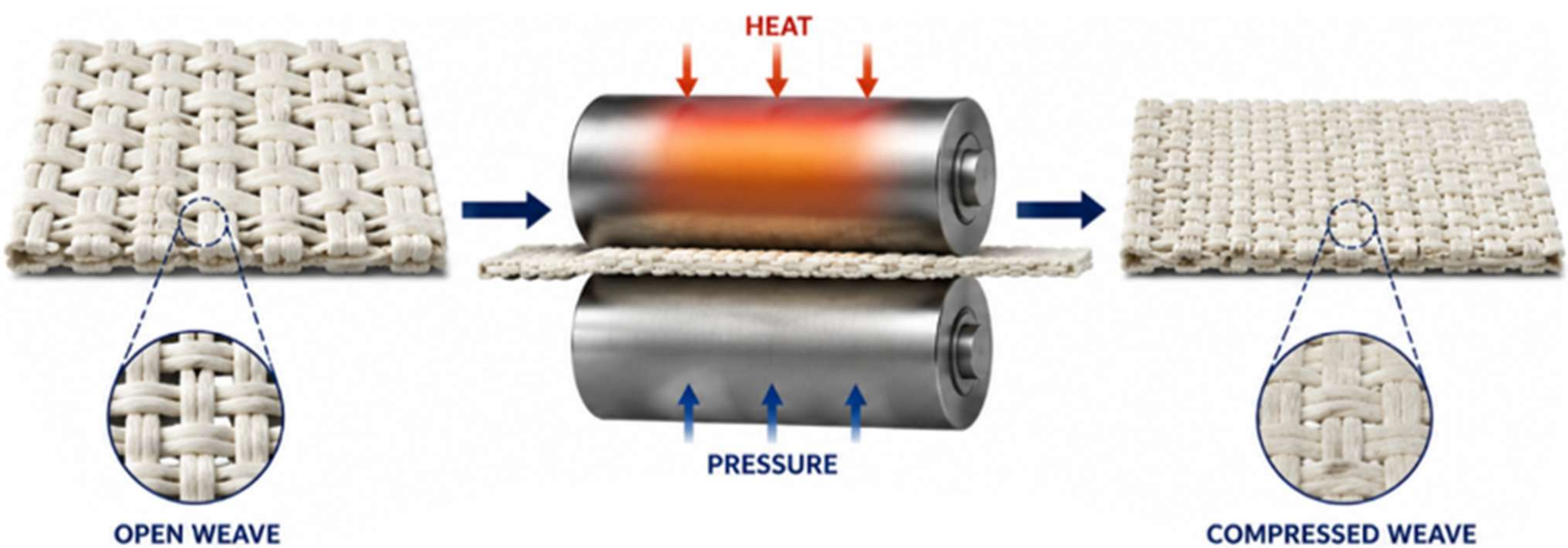
DUST PERFORMANCE Dust penetration, adhesion, uptake

Calendaring Process

Neat fabric
- Larger interstitial openings
- High air permeability
- Greater potential for dust penetration

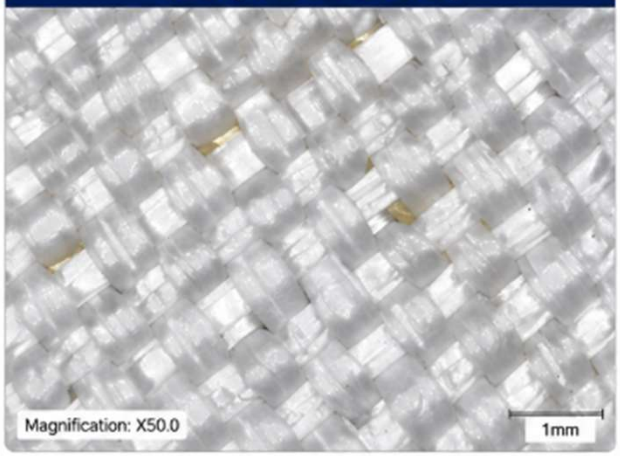
Calendaring
- Fabric fed through heated rollers under pressure
- Compresses and flattens yarns

Calendared Fabric
- Reduced interstitial openings
- Lower air permeability
- Improved resistance to dust

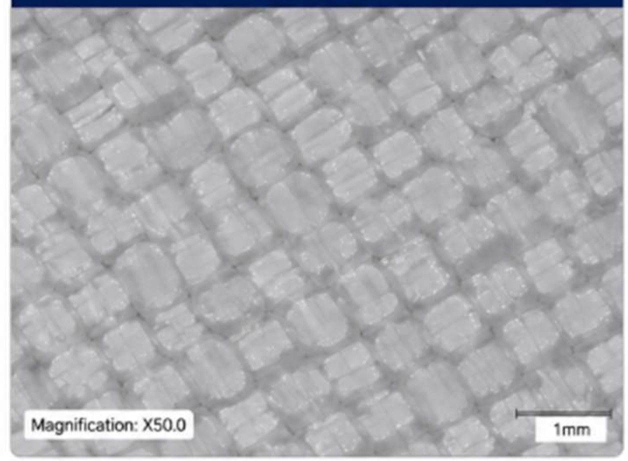


Ortho Structural Changes from Calendaring

NEAT (UNCALENDERED)



CALENDERED



OBSERVED STRUCTURAL CHANGES

- Yarns are flattened and “sintered” together
- Pores and interstitial openings are reduced
- Surface appears smoother and denser
- Weave pattern remains intact

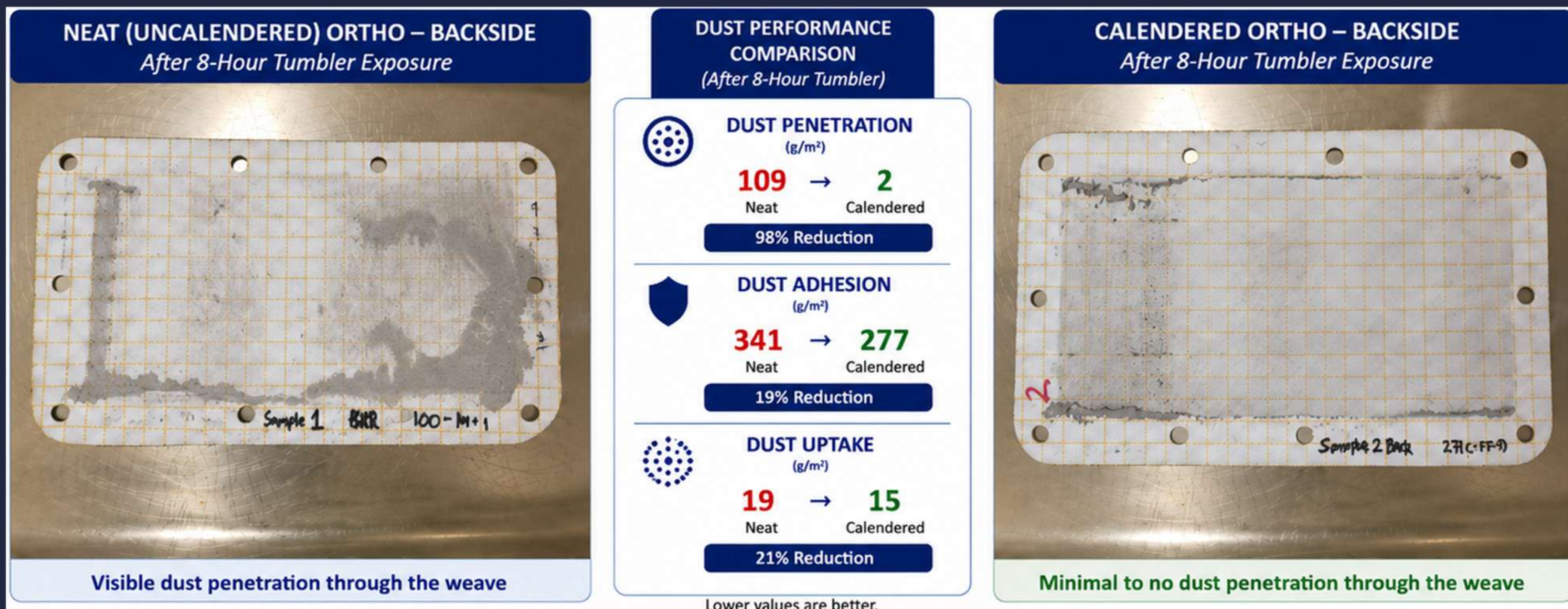
KEY IMPACTS AFTER CALENDARING (Ortho Fabric)

Thickness	↓	**28% Reduction**
Air Permeability	↓	**84% Reduction**
Stiffness (Cantilever)	↓	**21% Reduction**
Puncture	↓	**15% Reduction**

Tensile, Elongation, Tear, and Mass Remained the Same

Significantly reduced pore size while maintaining the woven architecture

Ortho Fabric Tumbler Dust Results

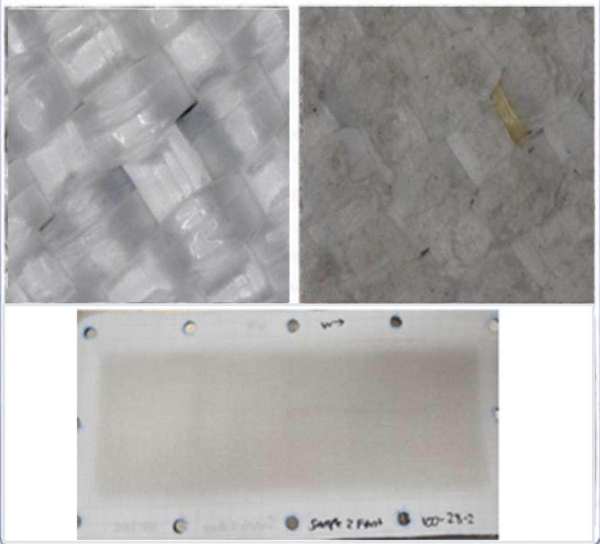


Calendaring delivers a 98% reduction in dust penetration while decreasing dust adhesion and uptake for Ortho 116

Did Calendaring Effect Ortho Durability?

NEAT ORTHO (UNCALENDERED)

PRE-TUMBLING | POST-TUMBLING (8 HOURS)



CALENDERED ORTHO

PRE-TUMBLING | POST-TUMBLING (8 HOURS)

POST TUMBLER TEST RESULTS (8 HOURS)

Property	Neat Ortho	Calendared Ortho	% Change (Neat → (Calendared)	Goal Value
Thickness (in)	0.020	0.021	+1%	<0.02
Areal mass (oz/yd²)	15.5	15.1	-3%	<14.8
Air Permeability (cfm@125 Pa)	12.7	1.1	-91%	<0
Cantilever Stiffness (μNm)	267	411	+54%	-
Strip Tensile (lbf/in)	297*	260	-12%	>400
Elongation (%)	15*	17	+13%	>8
Tongue Tear (lbf)	120	86	-28%	>100
Puncture (ozf)	84.8	63.2	-25%	>215
Simulant Penetrated (g/m²)	109	2	-98%	25 clean
Simulant Adhesion (g/m²)	341	277	-19%	<2.5
Simulant Uptake (g/m²)	19	15	-21%	<0.1

** Previously reported neat Ortho tensile strength and elongation from ICES-2025-56 differ from the values presented here.*

KEY CHANGES IN MECHANICAL PROPERTIES AFTER TUMBLING

Stiffness +54% (worse)

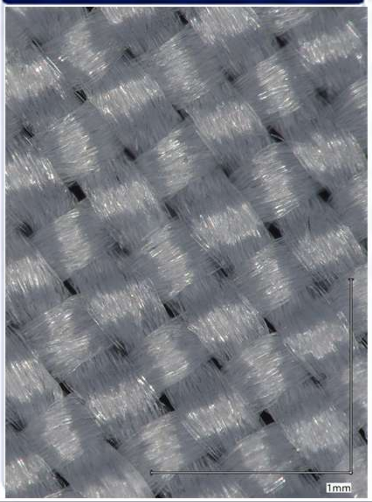
Strip Tensile -12% (worse)

Tongue Tear -28% (worse)

Puncture -25% (worse)

Thickness and mass remained the same.

Teflon™ T-162 Structural Changes from Calendaring

NEAT TEFLON T-162	CALENDARED TEFLON T-162
	

Property	Neat Teflon	Calendared Teflon	% Change (Cal vs. Neat)	Threshold Value	Goal Value
Thickness (in)	0.008	0.008	0%	<0.03	<0.02
Areal mass (oz/yd²)	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

KEY IMPACTS AFTER CALENDARING (Ortho Fabric)

Thickness	↓	28% Reduction
Air Permeability	↓	84% Reduction
Stiffness (Cantilever)	↓	21% Reduction
Puncture	↓	15% Reduction

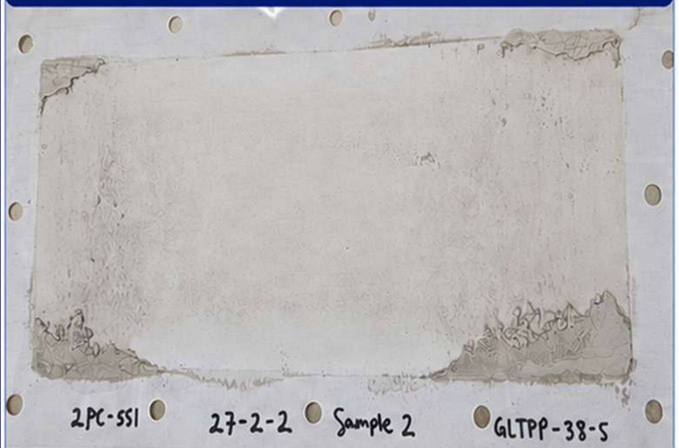
Tensile, Elongation, Tear, and Mass Remained the Same

KEY IMPACTS AFTER CALENDARING (Teflon T-162)

Thickness	=	0% Reduction
Air Permeability	↓	84% Reduction
Stiffness (Cantilever)	=	0% Reduction
Tensile	↓	5% Reduction
Elongation	↑	20% Increase

Teflon™ T-162 Tumbler Dust Results

NEAT (UNCALENDERED) TEFLON T-162 – BACKSIDE
After 8-Hour Tumbler Exposure



Visible dust penetration through the weave

DUST PERFORMANCE COMPARISON
(After 8-Hour Tumbler)

DUST PENETRATION
(g/m^2)

96.7 → 0.4
Neat Calendared

99.6% Reduction

DUST ADHESION
(g/m^2)

319 → Not Collected
Neat Calendared

Not Collected

DUST UPTAKE
(g/m^2)

20 → Not Collected
Neat Calendared

Not Collected

Lower values are better.

CALENDERED TEFLON T-162 – BACKSIDE
After 8-Hour Tumbler Exposure

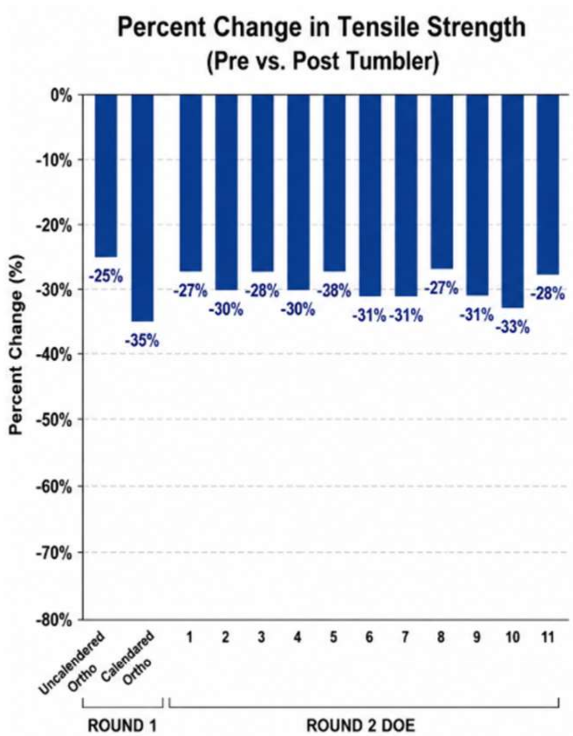
Minimal to no dust penetration through the weave

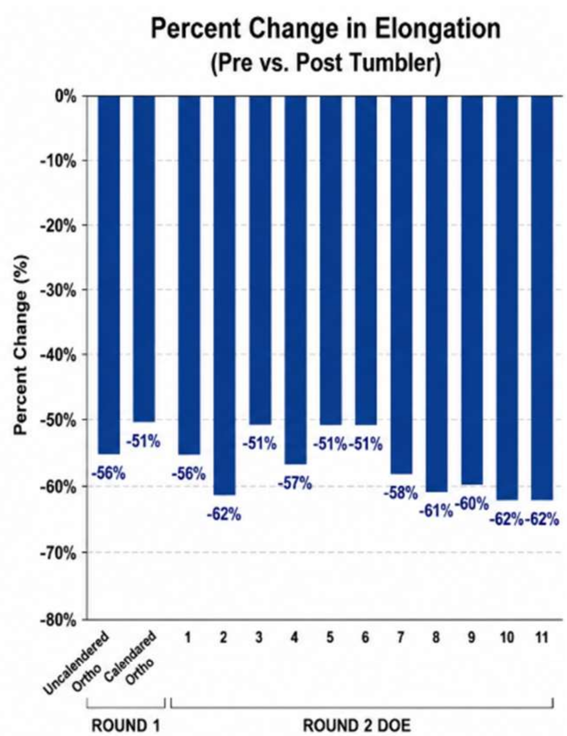
Calendaring delivers a 99% reduction in dust penetration for Teflon™ T-162

DOE Optimization - Durability

ROUND 1				
Condition (Bar)	Temp (°F)	Pressure (psi)	Speed (rpm)	Passes
Uncalendered Ortho	-	-	-	-
Calendered Ortho	215	50	1.5	1

ROUND 2 DOE				
Condition (Bar)	Temp (°F)	Pressure (psi)	Speed (rpm)	Passes
1	200	35	1.5	1
2	200	35	5	1
3	200	65	1.5	1
4	200	65	5	1
5	230	35	1.5	1
6	230	35	5	1
7	230	65	1.5	1
8	230	65	5	1
9	210	30	1.5	2
10	210	30	5	2
11	215	50	3.5	1





TENSILE LOSS

Neat Ortho vs. Calendared

-25% **-28% to -35%**

ELONGATION LOSS

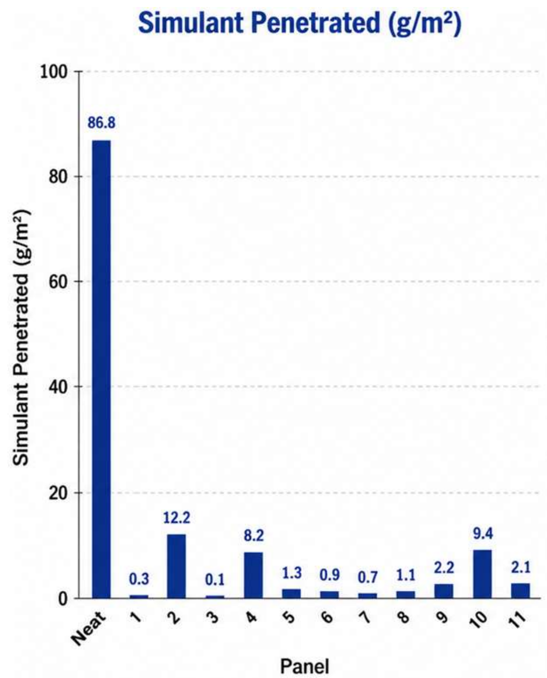
Neat Ortho vs. Calendared

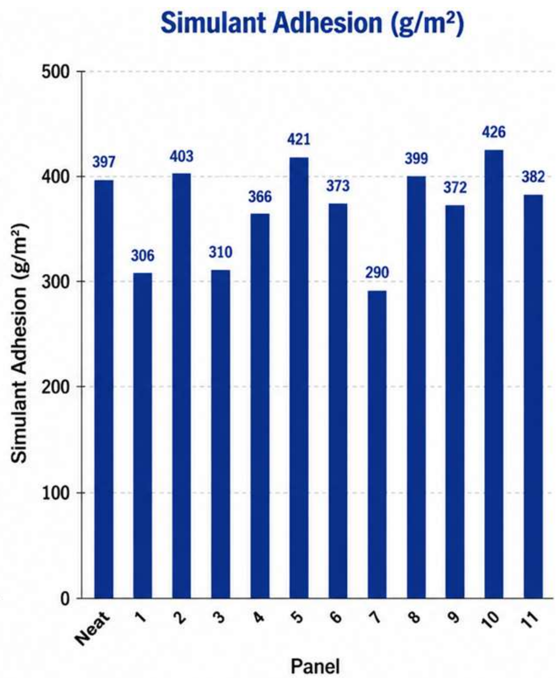
-56% **-51% to -62%**

DOE Optimization – Dust Penetration

ROUND 1				
Condition (Bar)	Temp (°F)	Pressure (psi)	Speed (rpm)	Passes
Uncalendered Ortho	-	-	-	-
Calendered Ortho	215	50	1.5	1

ROUND 2 DOE				
Condition (Bar)	Temp (°F)	Pressure (psi)	Speed (rpm)	Passes
1	200	35	1.5	1
2	200	35	5	1
3	200	65	1.5	1
4	200	65	5	1
5	230	35	1.5	1
6	230	35	5	1
7	230	65	1.5	1
8	230	65	5	1
9	210	30	1.5	2
10	210	30	5	2
11	215	50	3.5	1





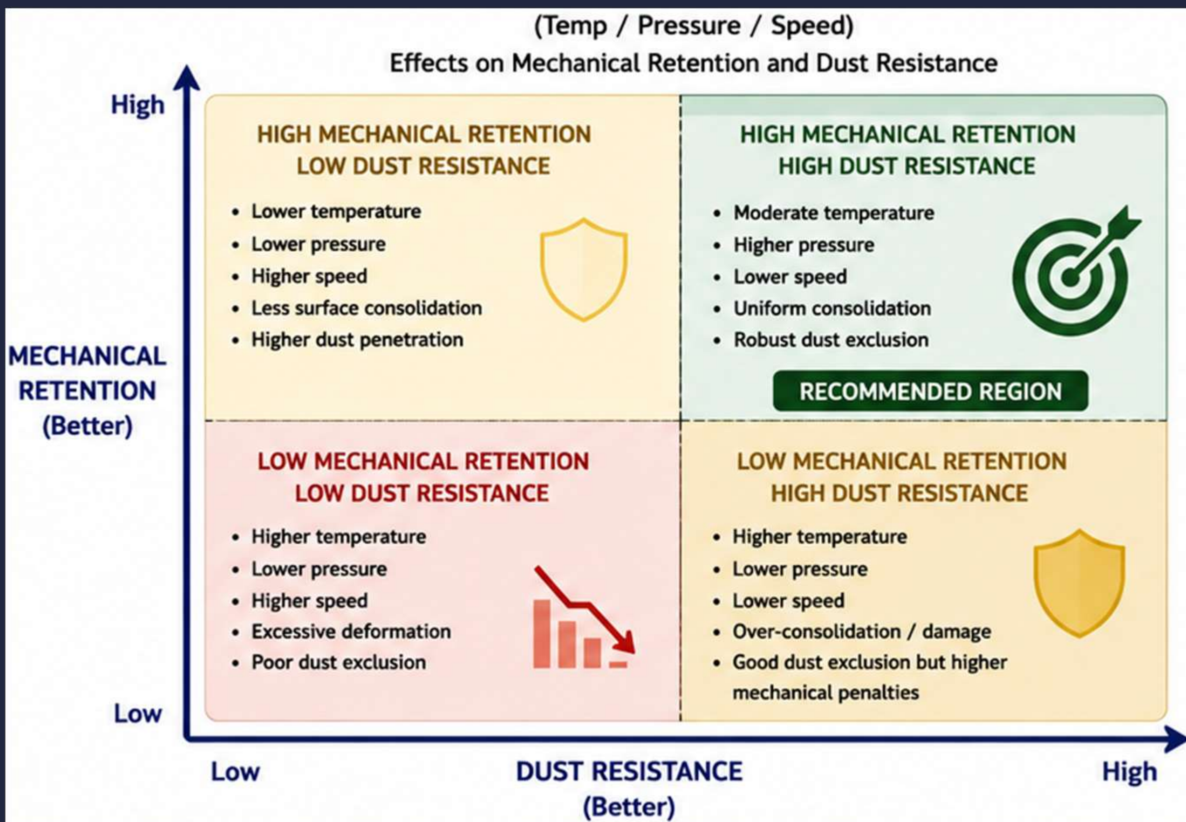
Dust Penetration

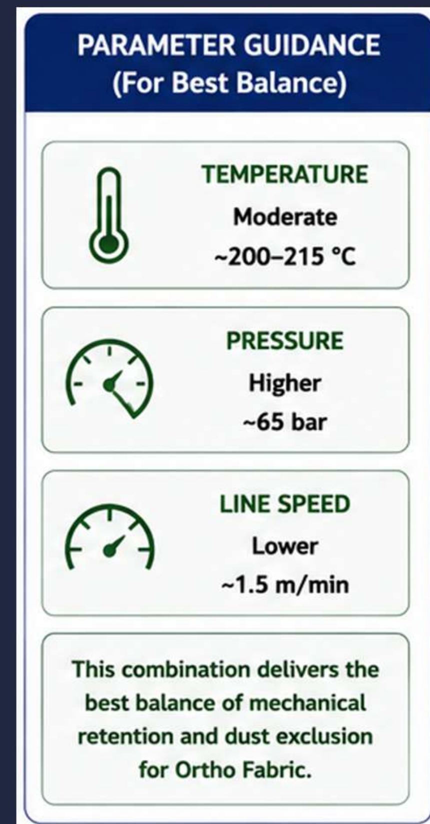
Neat Ortho vs. Calendared
86.6 g/m² **0.1 to 12.2 g/m²**

Dust Adhesion

Neat Ortho vs. Calendared
397 g/m² **290 to 426 g/m²**

Recommended Process

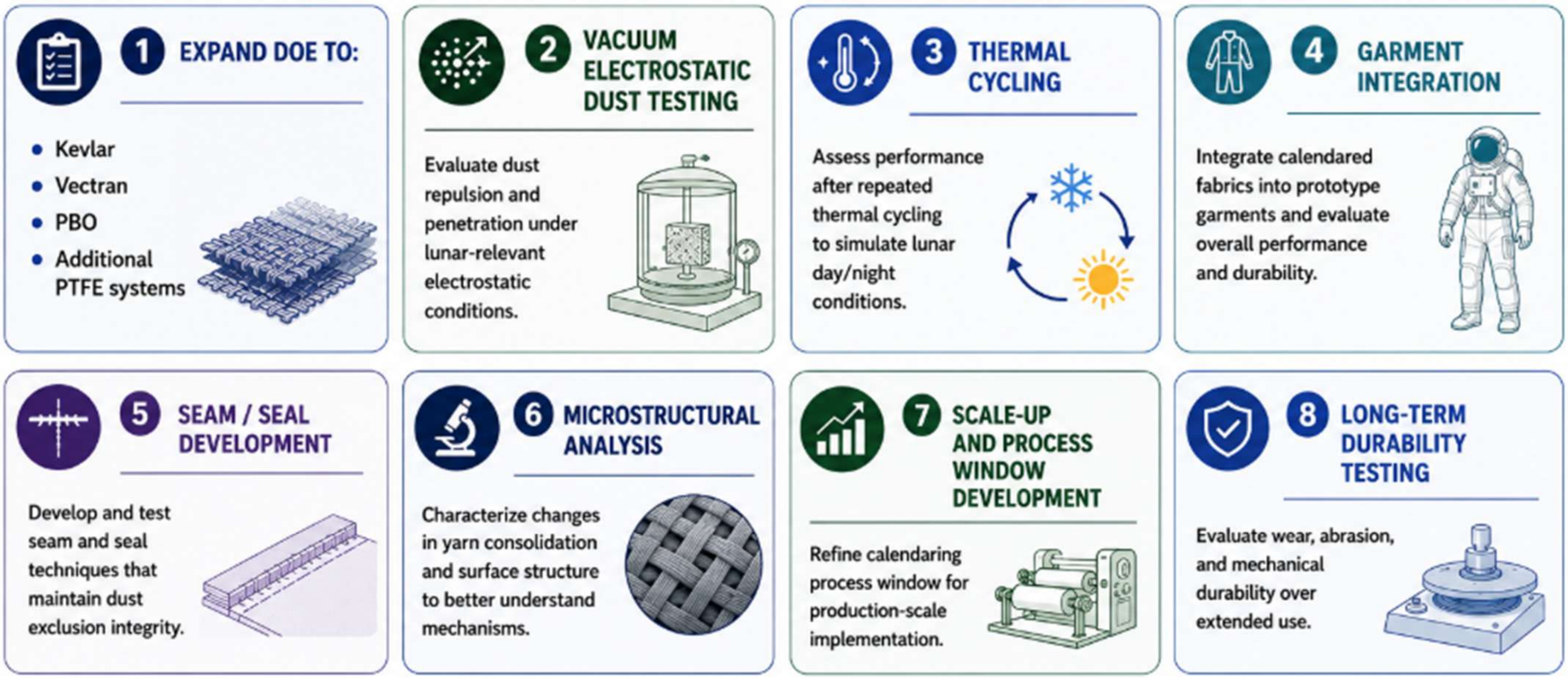




Conclusions

- Calendaring reduced dust penetration by ~995 across both fabrics
- Ortho 116 experienced modest mechanical penalties
  - 15% reduction in puncture resistance
- Teflon™ T-162 showed minimal mechanical impact
  - 5% reduction in tensile strength
- Air permeability and dust penetration are not always coupled
- Calendaring is a scalable post-processing technique on fabrics containing PTFE/ePTFE

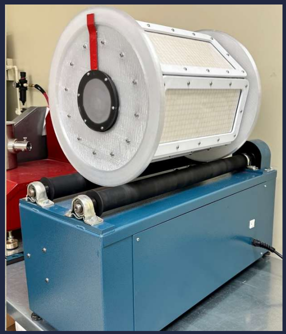
Future Work


1 EXPAND DOE TO:
Kevlar
Vectran
PBO
Additional PTFE systems
2 VACUUM ELECTROSTATIC DUST TESTING
Evaluate dust repulsion and penetration under lunar-relevant electrostatic conditions.
3 THERMAL CYCLING
Assess performance after repeated thermal cycling to simulate lunar day/night conditions.
4 GARMENT INTEGRATION
Integrate calendared fabrics into prototype garments and evaluate overall performance and durability.
5 SEAM / SEAL DEVELOPMENT
Develop and test seam and seal techniques that maintain dust exclusion integrity.
6 MICROSTRUCTURAL ANALYSIS
Characterize changes in yarn consolidation and surface structure to better understand mechanisms.
7 SCALE-UP AND PROCESS WINDOW DEVELOPMENT
Refine calendaring process window for production-scale implementation.
8 LONG-TERM DURABILITY TESTING
Evaluate wear, abrasion, and mechanical durability over extended use.


ADVANCED SUIT TEAM
NASA
JSC

Lunar Fabric Test Procedure

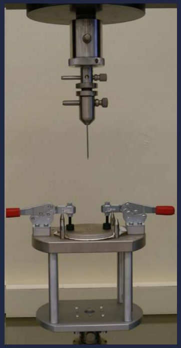
- Testing locations
  - NASA JSC:
    - ASTM: Tensile/Elongation, Cut, Puncture, Tear, Abrasion, Air perm, Flex Cracking, Stiffness, Emissivity, Absorptivity, Mass, Thickness, 3-point fold, Drape
    - NASA Custom: Rotary Tumbler, Hot/Cryo Cut, Cryo stiffness, Dusty Glovebox, Dusty TVAC
  - Other NASA Centers:
    - UV exposure, Ionizing radiation, Flammability, Off/Out gassing, ESD, Tribocharging, Particle Penetration, Yarn cryo tensile
  - Out of House:
    - Hot/Cryo tensile/tear/puncture/stiffness, LHe tensile, Cryo flex fatigue
- Ortho Fabric serves as baseline for comparisons
- Fabrics are compared to each other and baseline to inform down select decisions



Tumbler Test

Tumbler Panel

Fabric Test Strips



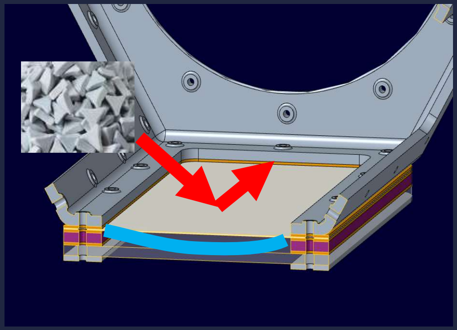
Puncture Test

Cryo Cut Test

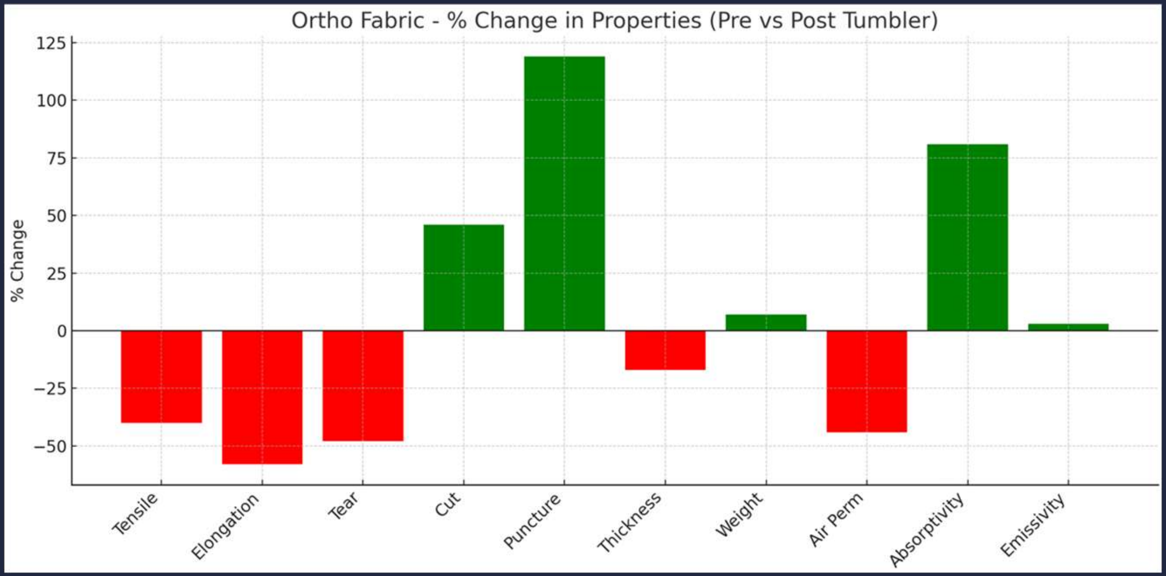
Cryo Flex Fatigue Test

Tear Test

Baselining Ortho: Abrasion Exposure



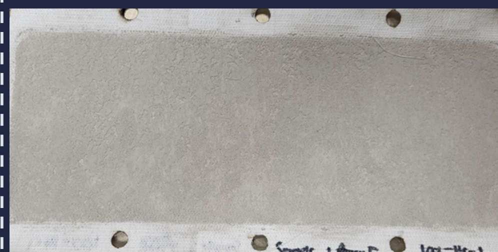
Ortho Fabric	Tensile (lbf)	Elongation (%)	Tear (lbf)	Cut (gf)	Puncture (ozf)	Thickness (in)	Weight (oz/yd^2)	Air Perm (CFM@125 PA)	Absorptivity	Emissivity
Pre Tumbler (BOL)	507	59	229	437	38.8	0.024	14.5	22.5	0.200	0.837
Post Tumbler (EOL)	302	25	120	637	84.8	0.02	15.49	12.7	0.362	0.866
% difference	40%	58%	48%	-46%	-119%	17%	-7%	44%	-81%	-3%

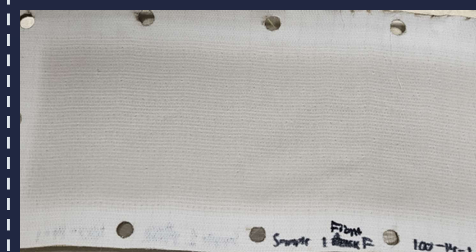


Baselining Ortho: Dust Exposure

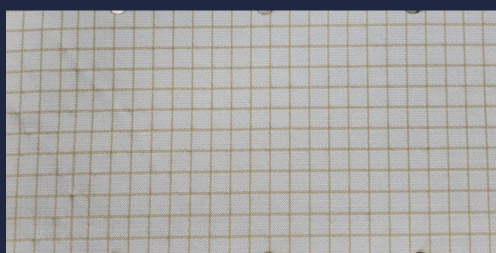
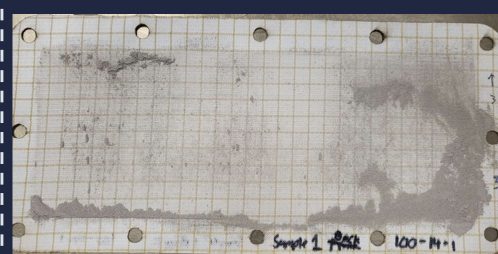
Pristine | **Post Tumble** | **Post Brushing** | **Post Vacuum**

Front



Back

Front Microscopy

Ortho Fabric 116				
Property	Avg. Post Tumbler	Max	Min	Std Dev.
Penetrated Simulant (g/m^2)	157	213	104	36.5
Simulant Adhesion (g/m^2)	284	282	81	78.3
Simulant Uptake (g/m^2)	19	33	14	5.4