

Challenges in Engineering PPE for Performance

Prof Ningtao Mao



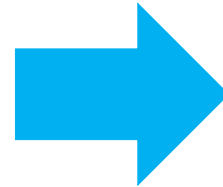
Which PPE ?

Hazards and Protection



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1. Cold;
2. Heat;
3. Wind;
4. Rain/Sea/Liquids;
5. CBR (Chemical, Biological and Radiation hazards)
6. Fire/High temperature;
7. Bullet/Knife/Projectile;
8. UV;
9. Others



1. Thermal insulation;
2. Cooling effect;
3. Windproof;
4. Water/Liquid proof;
5. CBR (Chemicals, Biological and Radiations) barriers
6. Fire/heat resistance;
7. Ballistic/stab resistance;
8. UV proof;
9. Others

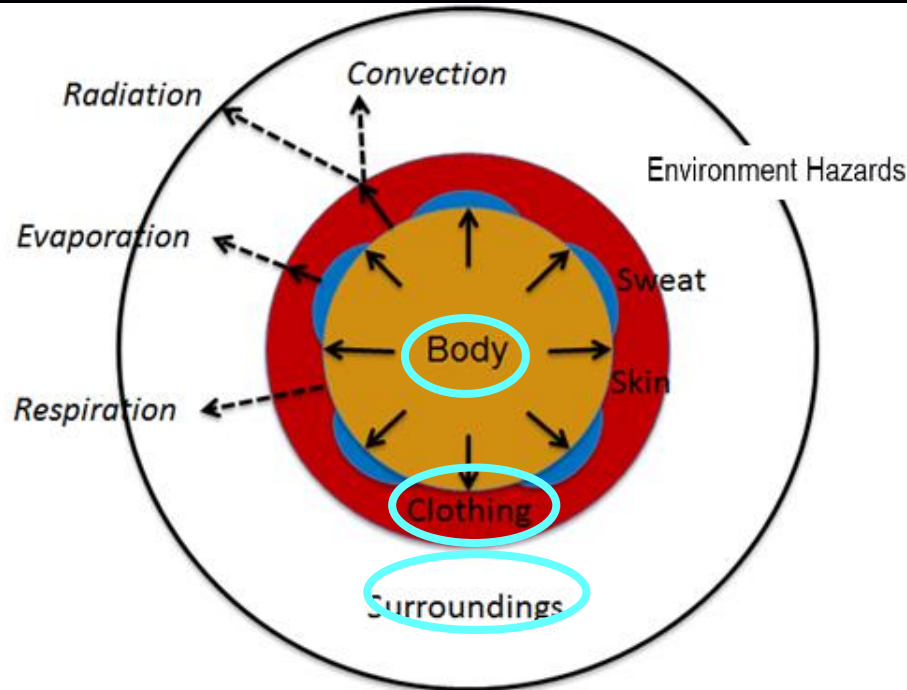
Personal Protective Equipment (PPE) is a System



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Industrial PPE



Firefighter's PPE



CNBR PPE



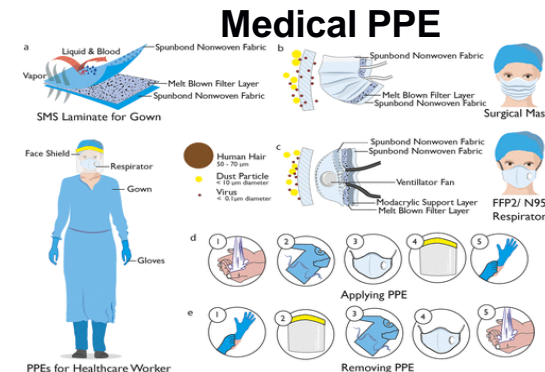
PPE for Cold Weather



High Temp PPE



Intelligent combat clothing "Warrior Web"



Medical PPE

a. Liquid & Blood Spunbond Nonwoven Fabric
 Vapor Melt Blown Filter Layer Spunbond Nonwoven Fabric
 SMS Laminate for Gown
 b. Spunbond Nonwoven Fabric
 Melt Blown Filter Layer Spunbond Nonwoven Fabric
 Surgical Mask
 c. Human Hair 50 - 70 μm
 Dust Particle 1 μm diameter
 Virus 0.1 μm diameter
 Spunbond Nonwoven Fabric
 Ventilator Fan
 Modacrylic Support Layer
 Melt Blown Filter Layer
 FFP2/ N95 Respirator
 d. 1. Hand hygiene 2. Glove application 3. Mask application 4. Gown application 5. Glove removal
 e. 1. Glove removal 2. Mask removal 3. Gown removal 4. Hand hygiene
 PPEs for Healthcare Worker
 Applying PPE
 Removing PPE

1. Protection

2. Comfort

(tactile, thermal, thermo-physiological comfort, sweating)

3. Mobility



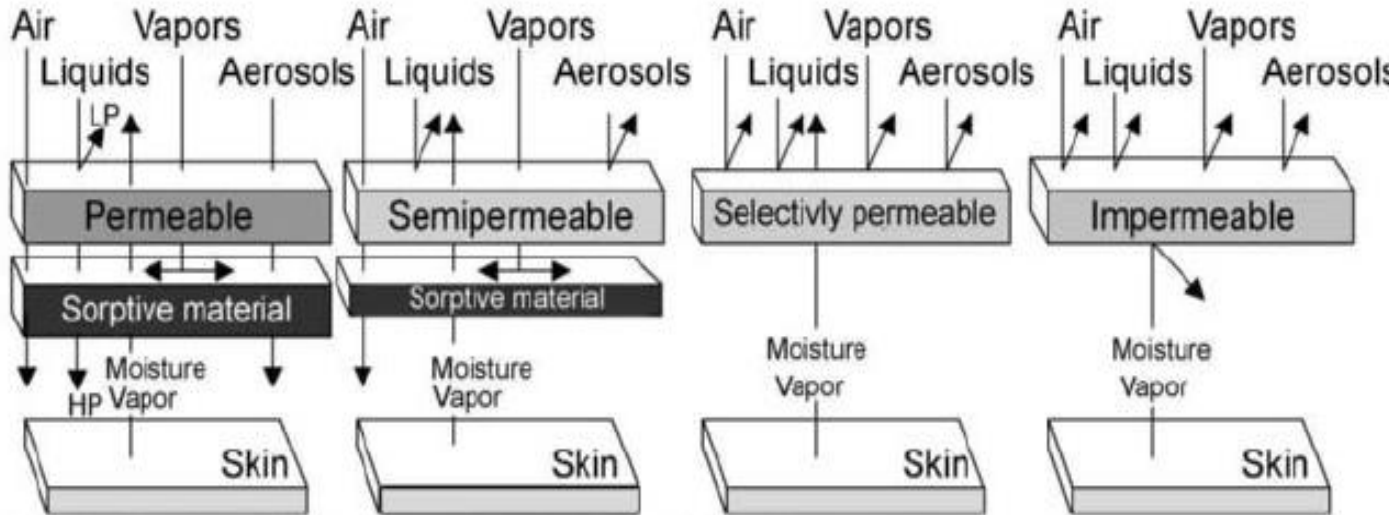
European (EU) Regulation 2016/425 and the PPE 2018 Regulations (SI 2018 No. 390)

USA Occupational Safety and Health Administration (OSHA): 29 CFR 1910.132

Achieving Protection and Comfort in PPE (examples of CBRN)



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LP: Low hydrostatic pressure HP: High hydrostatic pressure



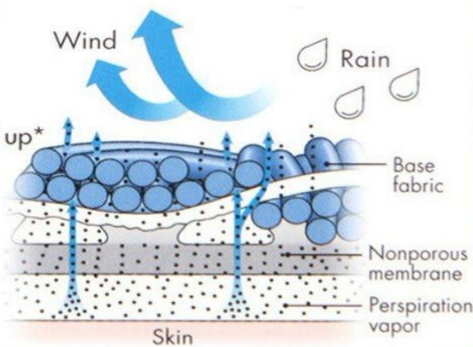
TORAYDELPHY 10000mm

Waterproofness:
5,000mmHzO and up

Moisture Permeability:
10,000g/m²/24hrs. and up*

Water Repellency:
80 points or higher
(after 20 wash cycles)

*B-1 inverted cup method
(JIS L1099 B-1)



Materials for Firefighter's Clothing



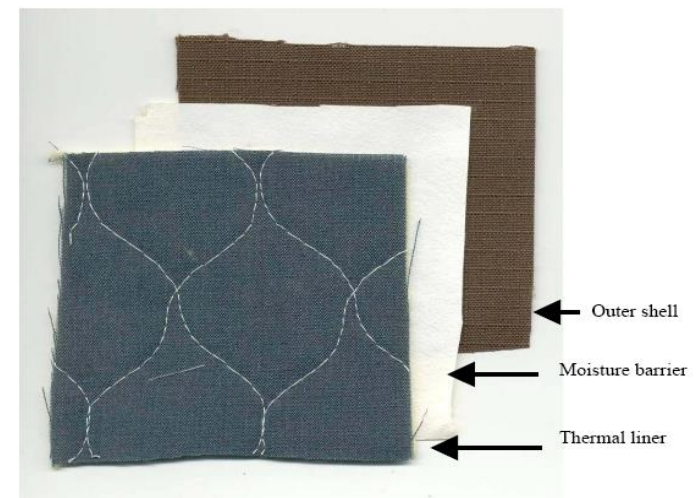
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Destructive Tests	Ensemble Elements Tested
Ensemble temperature measurements	All elements
Thermogravimetric Analysis	All elements
ASTM F 903: Standard Test Method for Resistance of Protective Clothing Materials to Penetration by Liquids ^a [35]	Moisture Barrier
ASTM F 1060: Standard Test Method for Thermal Protective Performance of Materials for Protective Clothing for Hot Surface Contact [36]	Thermal Liner
ASTM D 5034: Standard Test Method for Breaking Force and Elongation of Textile Fabrics (Grab Test) [37]	Outer shell
ASTM D 5733: Standard Test Method for Tearing Strength of Nonwoven Fabrics by the Trapezoid Procedure [38]	Moisture Barrier, Thermal Liner
Non-Destructive Tests	Ensemble Elements Tested
Optical Microscopy	Outer shell
Raman Spectroscopy	Outer shell
Digital Image Analysis	Outer shell
Colorimetry	Outer shell

Outer shell : consists of a blend of 60% Kevlar® (poly para-aramid) and 40% Nomex® (poly meta-aramid),

Moisture barrier is a PTFE membrane

The thermal liner consists of Nomex® face cloth and Kevlar® batting;

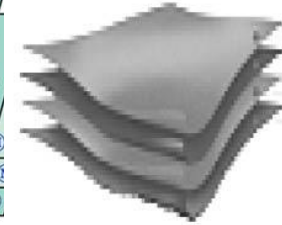
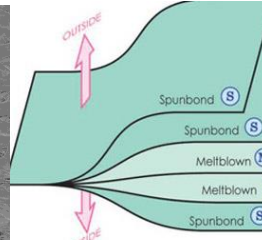
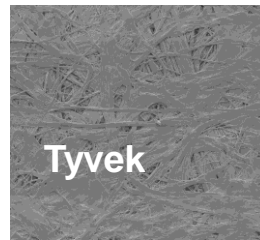


Fabrics Engineered for Protection and Comfort



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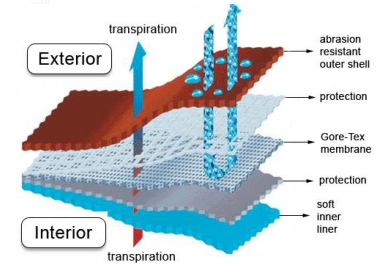
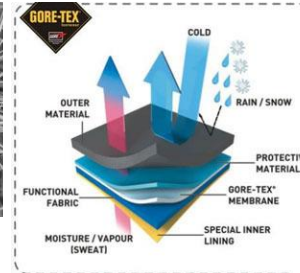
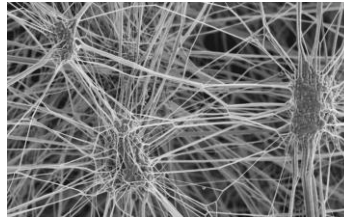
- Permeable textiles



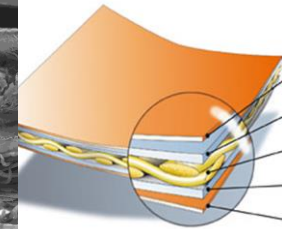
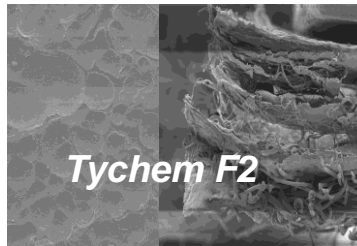
- Cotton non-woven
- Activated carbon
- Cotton non-woven
- Cotton Fabric

- Semipermeable films

(Gore-tex & monolithic PU film)



- Impermeable films

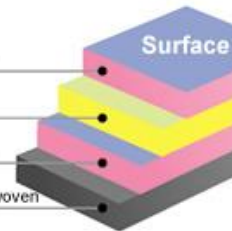


Special polyethylene

EVOH

Special polyethylene

Special polyethylene non-woven



- Clothing design

-Paramo

-Seam seals

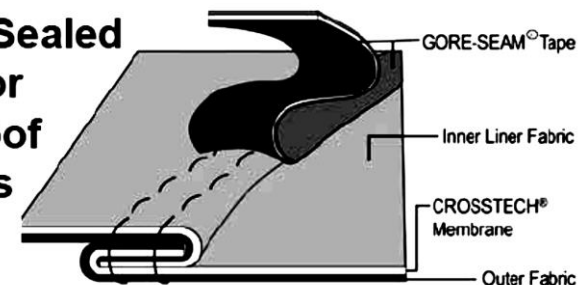
EN 343



KLASSE 3
= WASSERDAMPDURCHGANGS-
WIDERSTAND
(RET) < 20

KLASSE 3
= WASSERDURCHGANG
WIDERSTAND
> 13.000 PA
(NACH VORBEHANDLUNG)

Durably Sealed Seams for Waterproof Garments



Case Studies: Engineering Workwear for Cold Weather



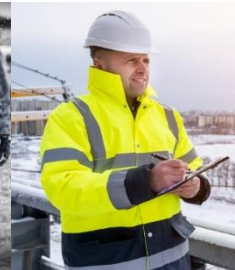
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The minimum temperature is either at least 16°C, or 13°C for work involving rigorous physical effort.

- appropriate PPE,
- more frequent rest breaks,
- delay work until warmer time;

(for indoor working environment)

(for outdoor working environment)



How cold is cold ? and What do we wear in winter ?



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9news.com **DRESSING FOR COLD WEATHER**



Is this guidance reliable ?

WIND CHILL TEMPERATURE INDEX

Frostbite Times are for Exposed Facial Skin

Air Temperature (°C)

Wind Speed (km/h)	5	0	-5	-10	-15	-20	-25	-30	-35	-40	-45	-50
5	4	-2	-7	-13	-19	-24	-30	-36	-41	-47	-53	-58
10	3	-3	-9	-15	-21	-27	-33	-39	-45	-51	-57	-63
15	2	-4	-11	-17	-23	-29	-35	-41	-48	-54	-60	-66
20	1	-5	-12	-18	-24	-30	-37	-43	-49	-56	-62	-68
25	1	-6	-12	-19	-25	-32	-38	-44	-51	-57	-64	-70
30	0	-6	-13	-20	-26	-33	-39	-46	-52	-59	-65	-72
35	0	-7	-14	-20	-27	-33	-40	-47	-53	-60	-66	-73
40	-1	-7	-14	-21	-27	-34	-41	-48	-54	-61	-68	-74
45	-1	-8	-15	-21	-28	-35	-42	-48	-55	-62	-69	-75
50	-1	-8	-15	-22	-29	-35	-42	-49	-56	-63	-69	-76
55	-2	-8	-15	-22	-29	-36	-43	-50	-57	-63	-70	-77
60	-2	-9	-16	-23	-30	-36	-43	-50	-57	-64	-71	-78
65	-2	-9	-16	-23	-30	-37	-44	-51	-58	-65	-72	-79
70	-2	-9	-16	-23	-30	-37	-44	-51	-58	-65	-72	-80
75	-3	-10	-17	-24	-31	-38	-45	-52	-59	-66	-73	-80
80	-3	-10	-17	-24	-31	-38	-45	-52	-60	-67	-74	-81

FROSTBITE GUIDE

- Increasing risk of frostbite for most people in 10 to 30 minutes of exposure
- High risk for most people in 5 to 10 minutes of exposure
- High risk for most people in 2 to 5 minutes of exposure
- High risk for most people in 2 minutes of exposure or less

Performance requirements of garments for cold weather



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- Wind** – Windproof
- Wet and ice** – Waterproof
- Low temperature** – Thermal Insulation
- Sweating** – Breathability
- Winter darkness** – High visibility



Cold Stress:

- Less likely to perform well, and
- More likely to behave unsafely

Windproofness ??

-- Air permeability



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WHICH ONE?



Water repellency or Waterproofness ??

-- Level of hydrostatic head



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Up To 5,000mm:

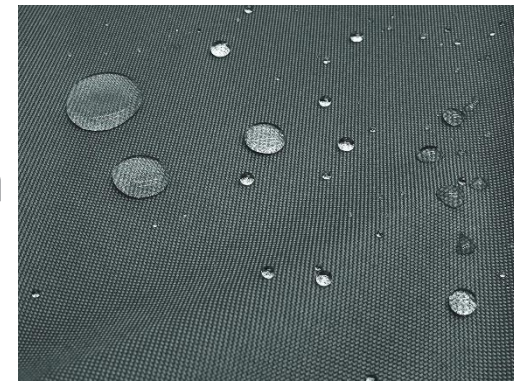
Light Rain

5,000mm - 10,000mm:

Average to Heavy Rain

10,000mm & Above:

Very Heavy Rain



Touch wood or touch ice ?

-- wet in winter is dangerous



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Contact factor (or thermal penetration coefficient) (F_c)

$$F_c = \sqrt{\rho c k}$$

ρ is the material density (kg/m^3), c – specific heat capacity (J/kgK); k – thermal conductivity ($\text{J/m}^2\text{Ks}^{0.5}$)

Material	Thermal conductivity λ (W / m K)	Specific heat c (10^3 J / kg K)	Contact factor F_c ($10^3 \text{ J / s}^{0.5} \text{ m}^2 \text{ K}$)
Aluminium	180	0,90	21,2
Brasses	85,5	0,38	16,9
Steel	14,8	0,46	7,27
Concrete	2,43	0,92	2,35
Ice	2.2	2.11	2.04
water	0.54	4.20	1.51
air	0.024	1.01	0.0056



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Thermal Insulation Performance of Textile Materials



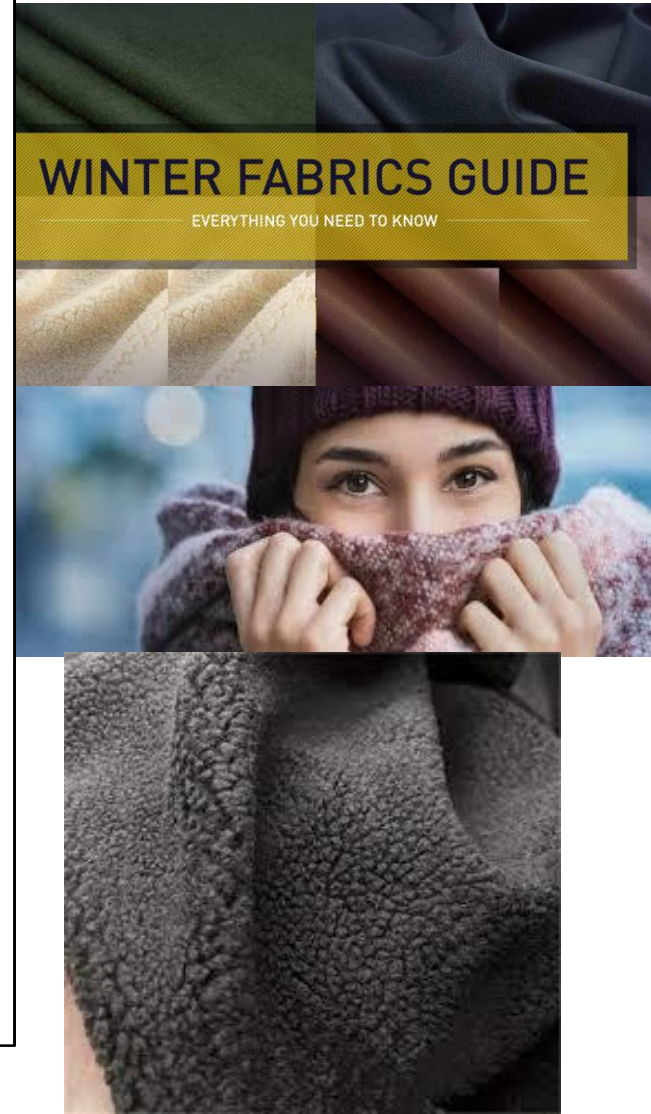
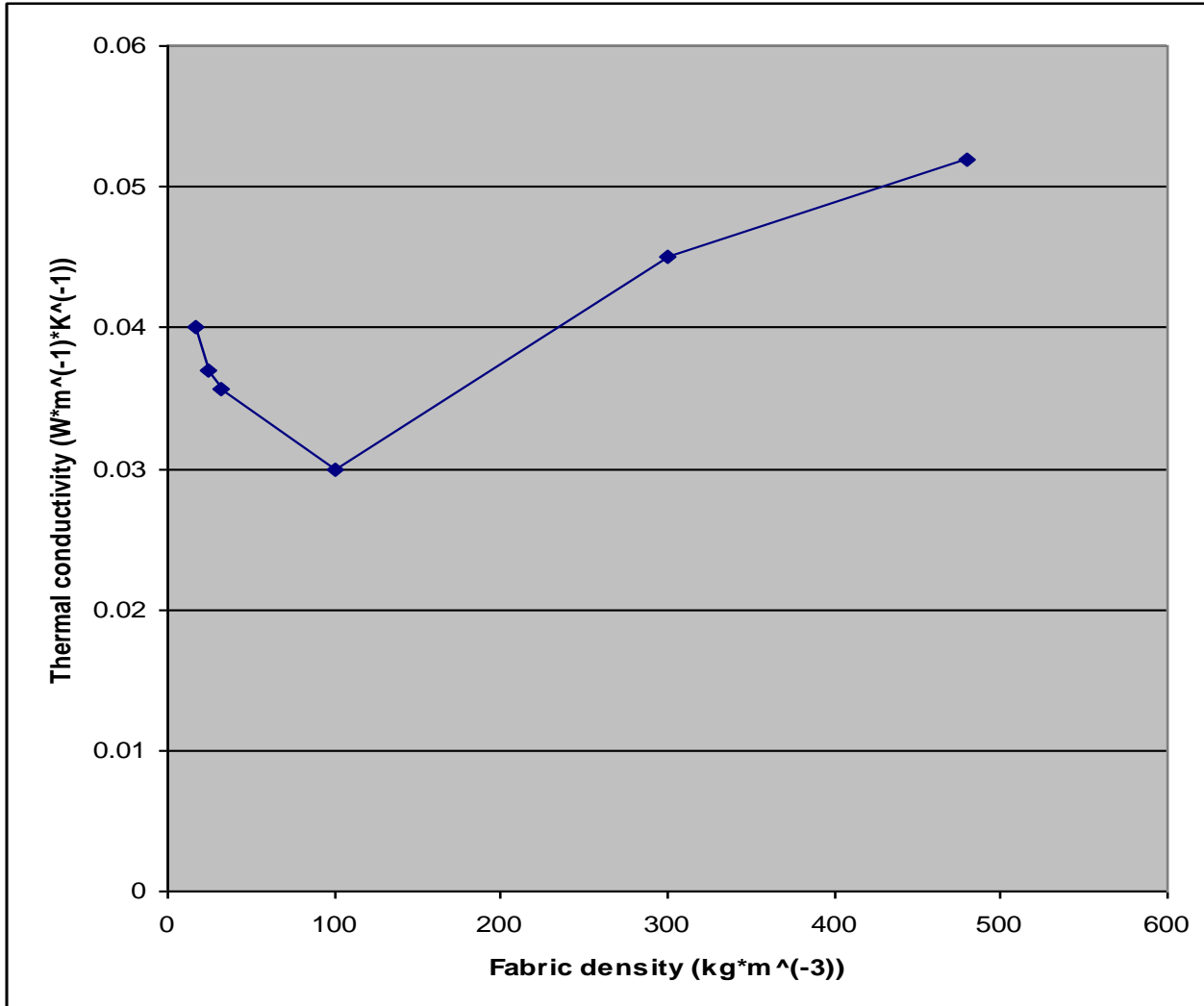
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Thermal resistance (m ² KW ⁻¹)		Materials	Density (Kg/m ³)	Thermal Conductivity (W/m*K)	Source of data		
$R_f (m^2 K/W) = \frac{L(mm) * 10^{-3}}{k(Wm^{-1} K^{-1})}$		Nylon 6 fibre [^]	1140	0.25	Morton and Hearle ^[i]		
		PET fibre [^]	1390	0.14			
		PP fibre [^]	910	0.12			
		PE fibre [^]	920	0.34			
		PVC fibre [^]	1360	0.16			
		Silk pad [^]	500	0.05			
		Cotton pad [^]	500	0.071			
		Wool pad [^]	500	0.054			
		1 Tog = 0.1 m²KW⁻¹		Silver [⊖]			406
Lightweight duvet: 4.5 tog	Air (25 ⁰ C) [⊖]			1.29	0.024		
	Water [⊖]			1000	0.58		
Mid weight duvet: 9.0-10.5 tog	Hairfelt [⊖]			100	0.05		
	Wool felt [⊖]			300	0.071		
Winter duvet: 12-13.5 tog	Loose Wool [⊖]			100	0.03		
	Wool felt [⊖]			320	0.047	ASHRAE ^[iii]	
	Wool keratin			1300	0.20	Baxter ^[iv]	

Air, Air, Still Air !!



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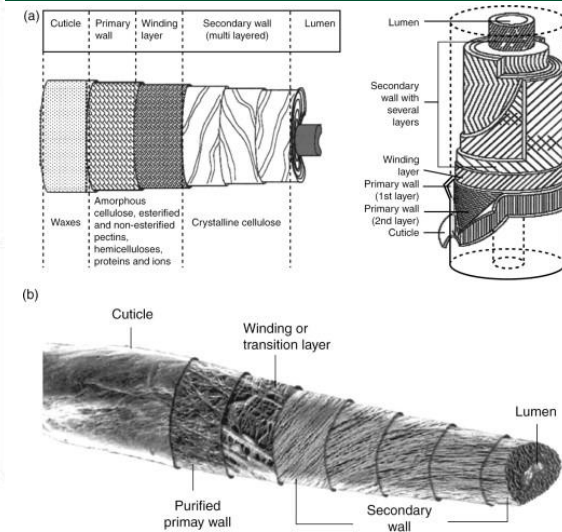
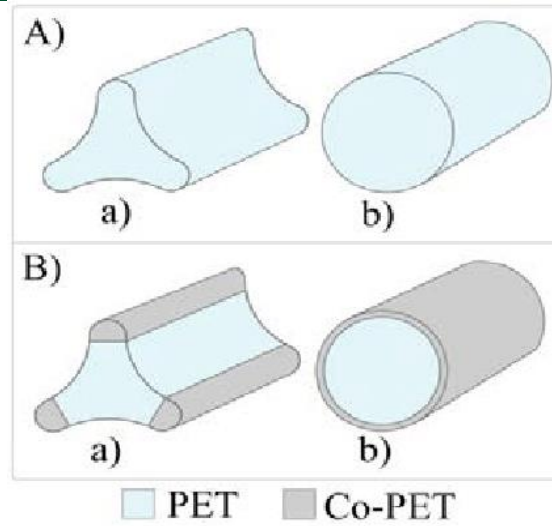


Playing with Air (1)

--- High Loft Nonwovens



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Wool is special !



Playing with Air (2)

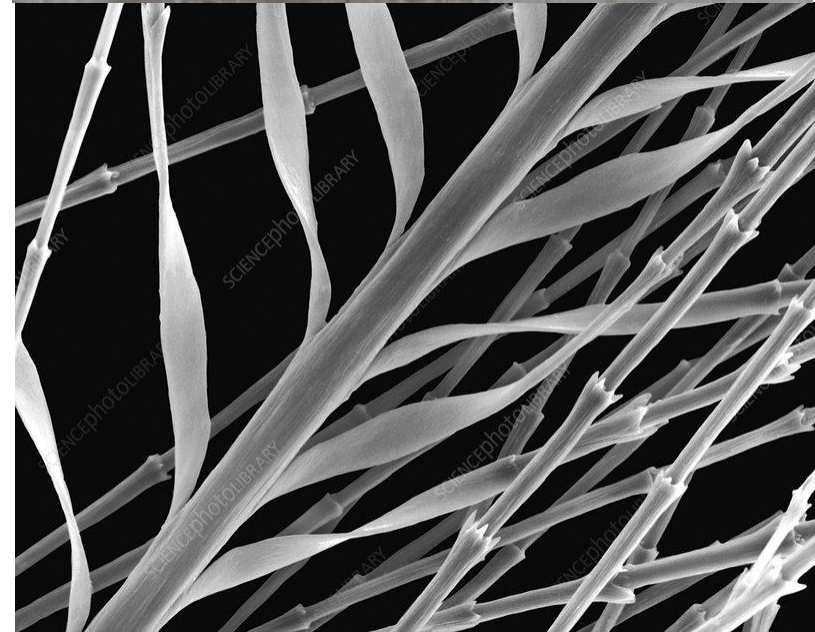
Eider, Goose & Duck Down ?



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Moorer WRIGHT-C
£20,550



Playing with Air (3)

--- Kapok Fibre



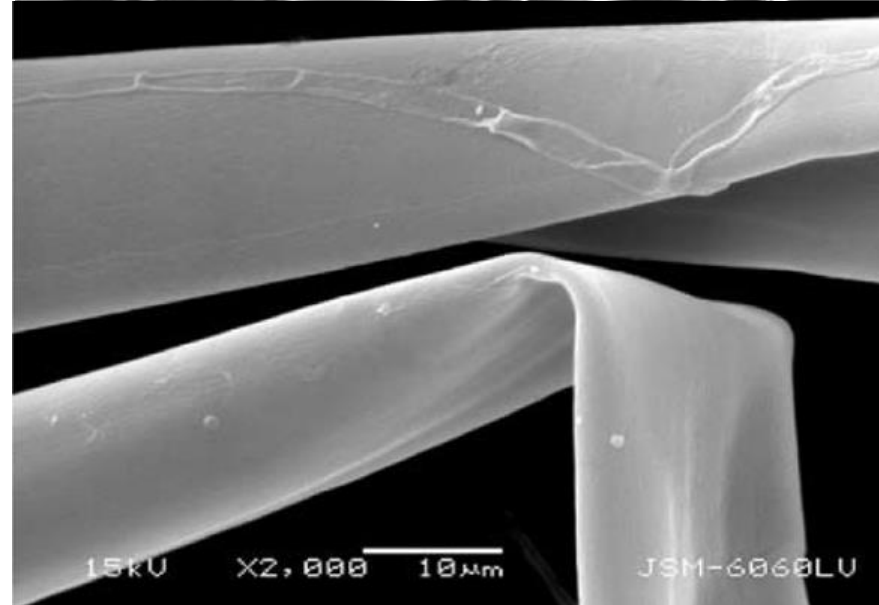
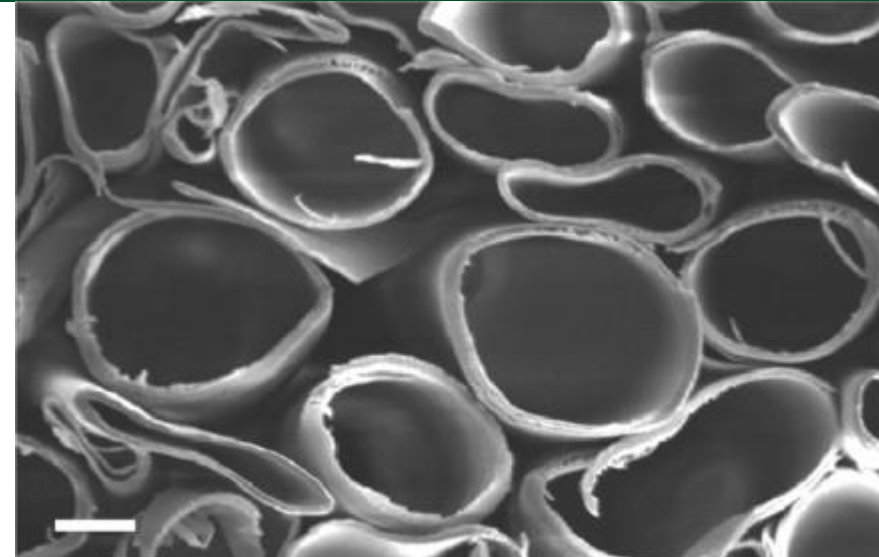
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Natural hollow fibres

70–80% of air;

Density of cell wall: 1.474 g/cm^3 ;

Density of fibre: 0.384 g/cm^3

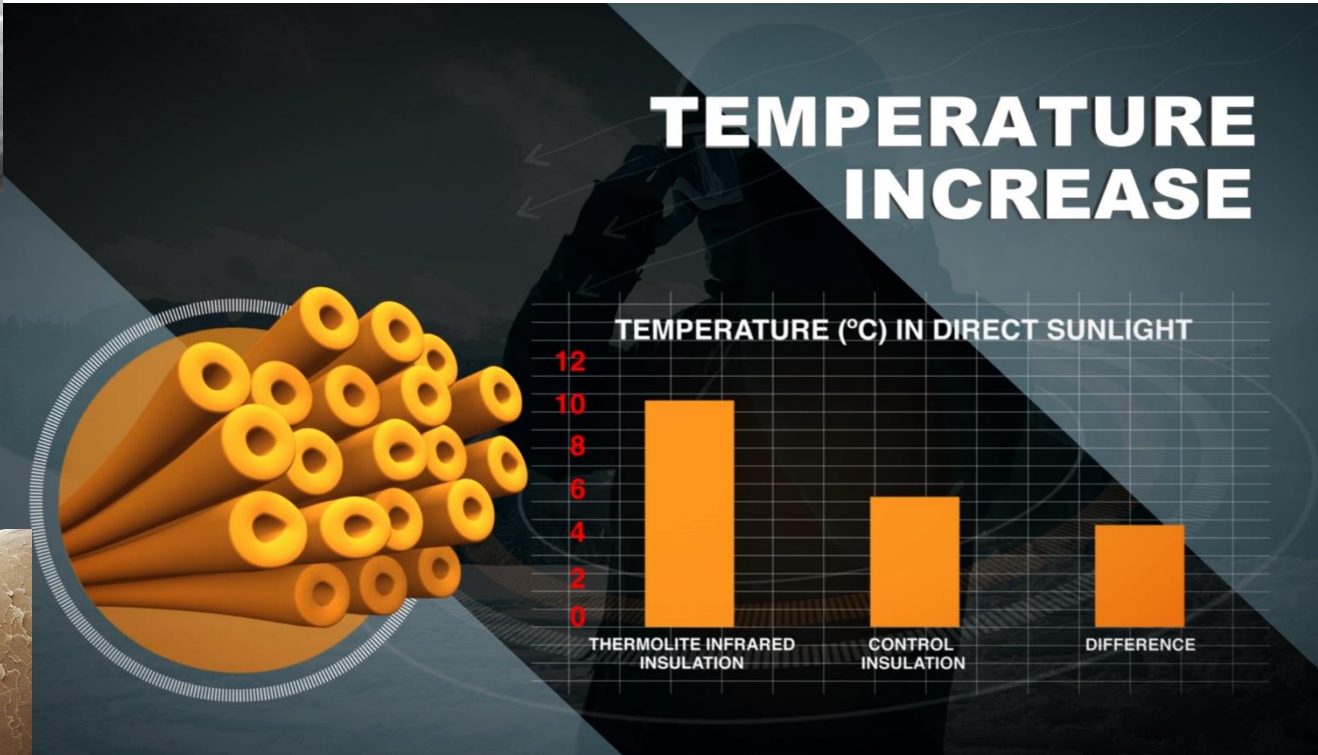


Play with air (4)

-- Hollow fibres learnt from nature



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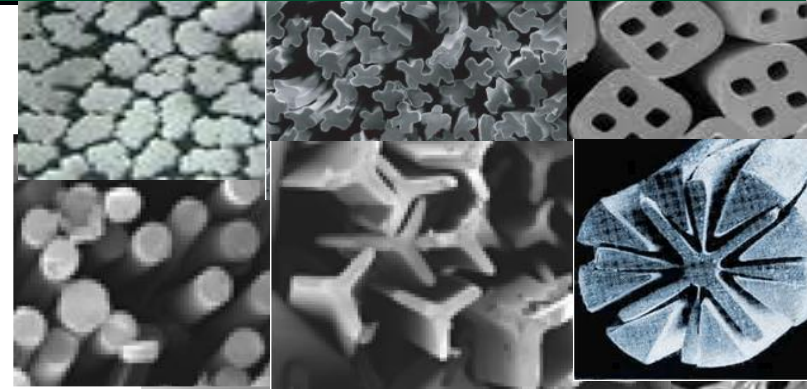
PrimaLoft, Thermolite

More engineered fibres available, could they be intelligent ?

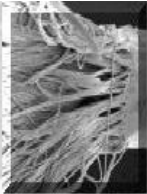


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Fibre composition and structures:
(diameter, cross-section, surface morphology, surface energy, hydrophobic/ hydrophilic, etc)



STRIPED



600 ISLANDS-IN-THE-SEA



16 SEGMENT PIE



HOLLOW SEGMENTED PIE



TRILOBAL



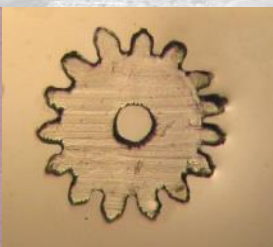
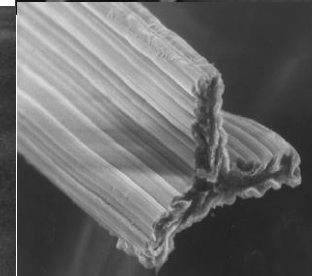
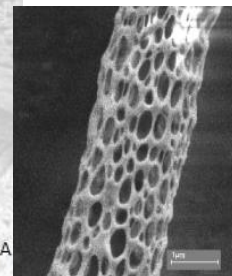
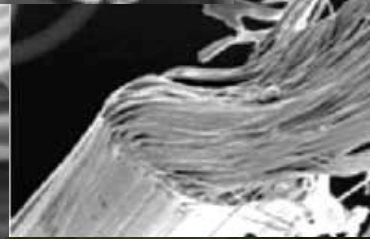
SHEATH/CORE



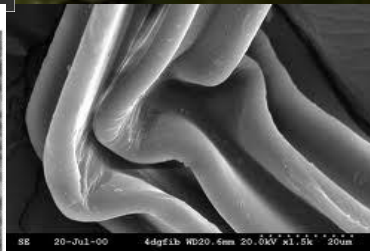
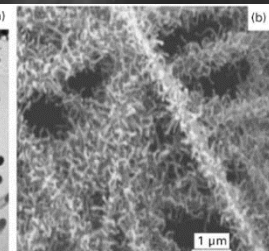
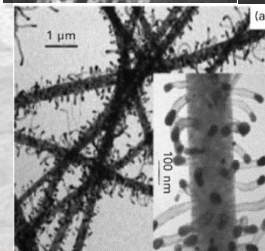
37 Islands-in-the-sea



64 ISLANDS-IN-THE-SEA



Pretty Picture



Playing with Air (5)

---- Intelligent Insulation



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Ralph Lauren



AS TEMPERATURE RISES,
THE INSULATION FLATTENS



Better than Air

– Aerogel materials



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- 99% air;
- Thermal conductivity: as low as 0.014 - 0.017;



Too Fragile
Health and Safety ??

Playing with Exothermic Heat

--- Smart yarn structure in HEATTECH

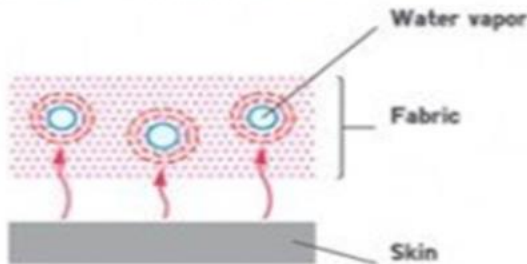


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The technology behind HEATTECH

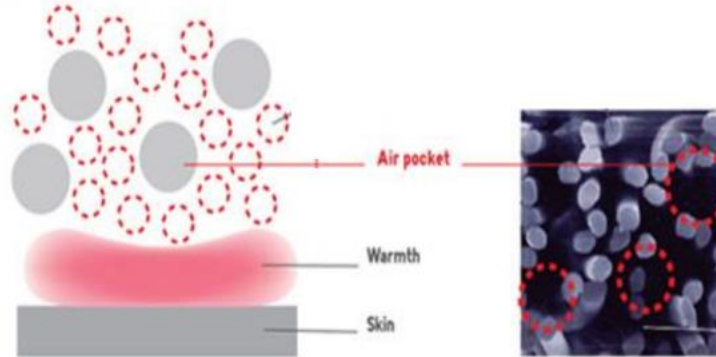
Heat generation

When HEATTECH absorbs body moisture, the droplets actually generates heat!



Heat retention

Air pockets between the fibres retain body warmth generated by HEATTECH moisture absorption.



Moisture control

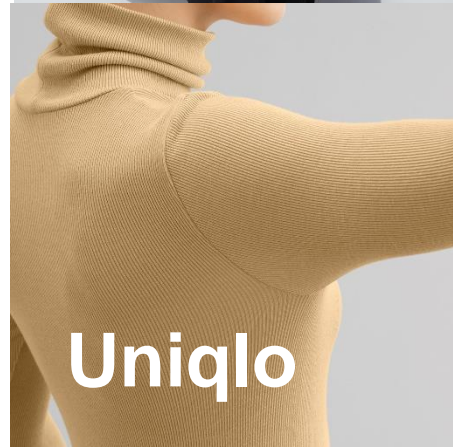
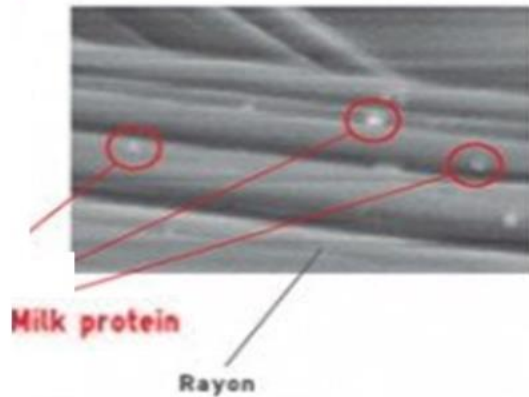
HEATTECH quickly absorbs and diffuses moisture. (Men only.)

Odour control

A special antibacterial agent in HEATTECH minimises odours.

Stretchable comfort

HEATTECH stretches to give you the perfect fit and exceptional comfort.



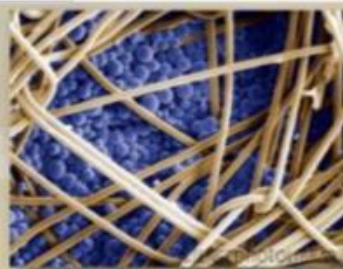
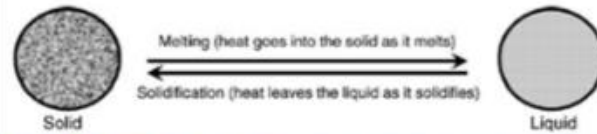
Uniqlo

Playing with Latent Heat

--- Phase Change Materials (PCM)



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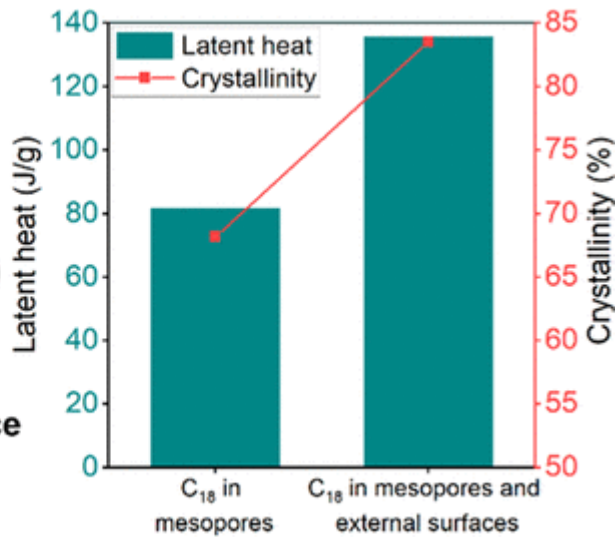
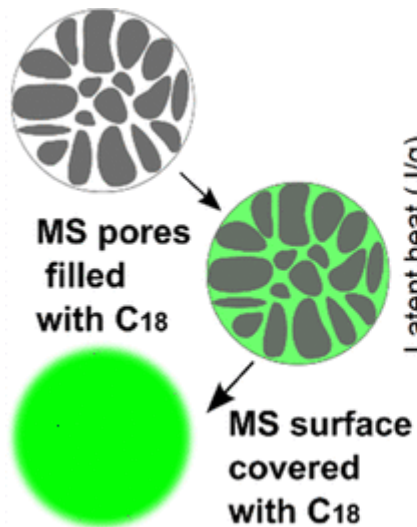
Outlast Thermo-molecules as a coating on textiles



Outlast Thermo-molecules locked into the textile fiber



In order to incorporate PCM in a specific textile product, it is first encapsulated.



Playing with Infra Red

-- Reflection and Absorption

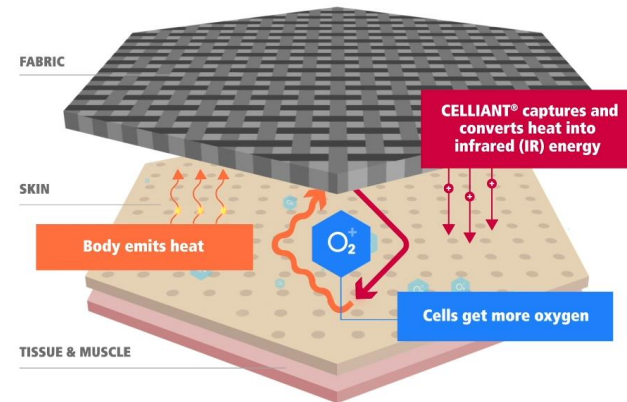
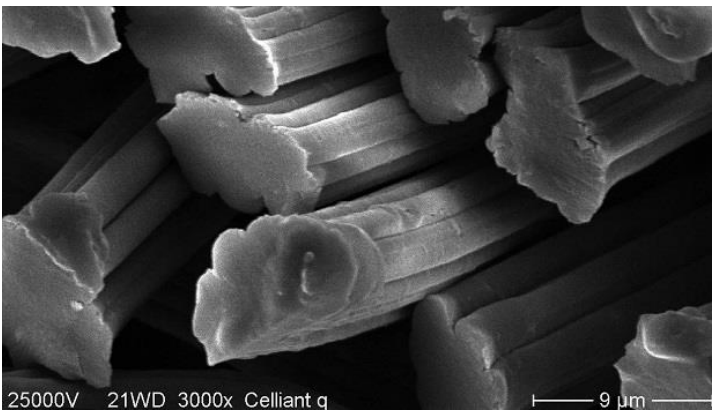


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Aluminum foil REFLECTs 95% of infrared rays



Celliant from Kelheim: Mineral particles embedded in viscose fibres to capture and convert body heat into infrared

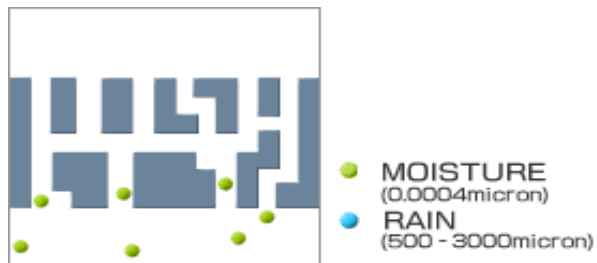
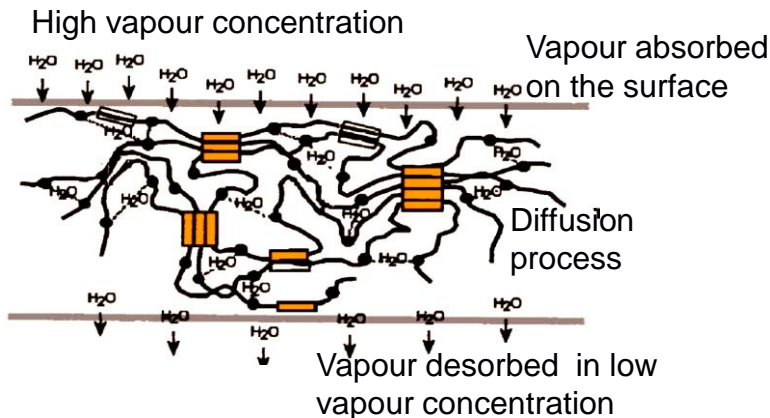


Carbon Black: Absorption of infrared and convert it into heat ??

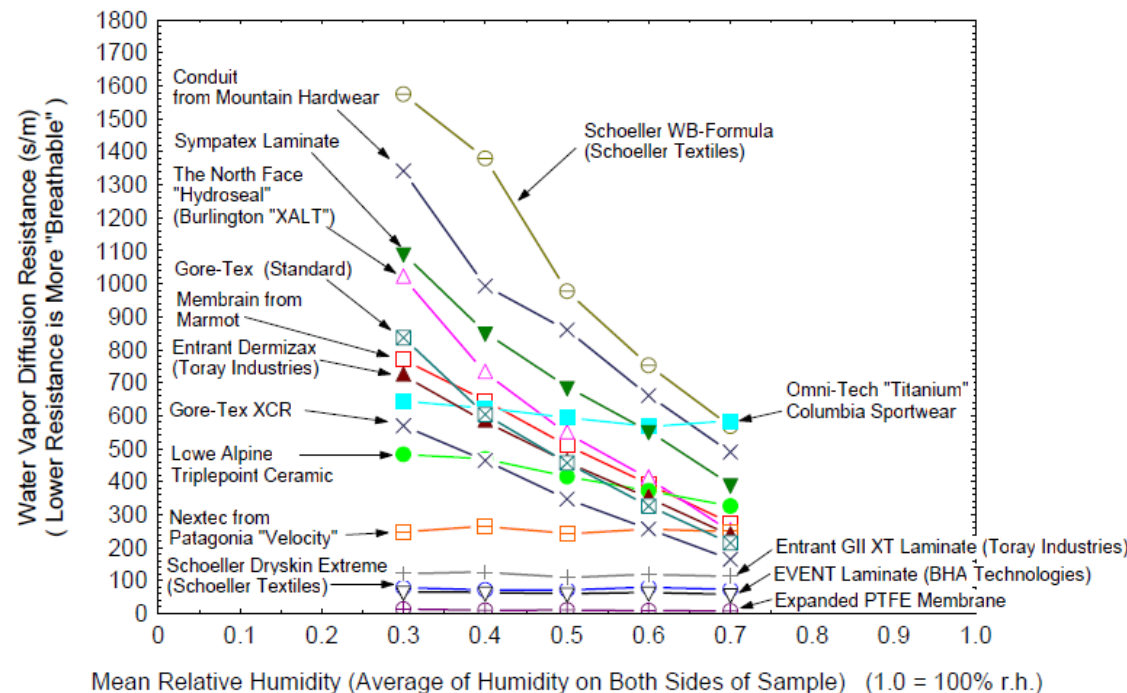


Grading of Fabric Breathability

Water-vapor resistance, R_{et} ($m^2 \cdot Pa/W$)	Grade	Classification
Water-vapor resistance, $R_{et} < 6$	5	Excellent
$6 \leq$ Water-vapor resistance, $R_{et} < 13$	4	Very Good
$13 \leq$ Water-vapor resistance, $R_{et} < 27$	3	Good
$27 \leq$ Water-vapor resistance, $R_{et} < 40$	2	Moderate
$40 \leq$ Water-vapor resistance, $R_{et} < 50$	1	Fair



"Breathability" Comparison of Commercial Outerwear Shell Layers



Water-vapour resistance, R_{et} ($m^2 P_a W^{-1}$)

Can we biomimic the unique performance of natural materials ?

Can we make PPE a smart system, no matter proactive, active or passive?

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