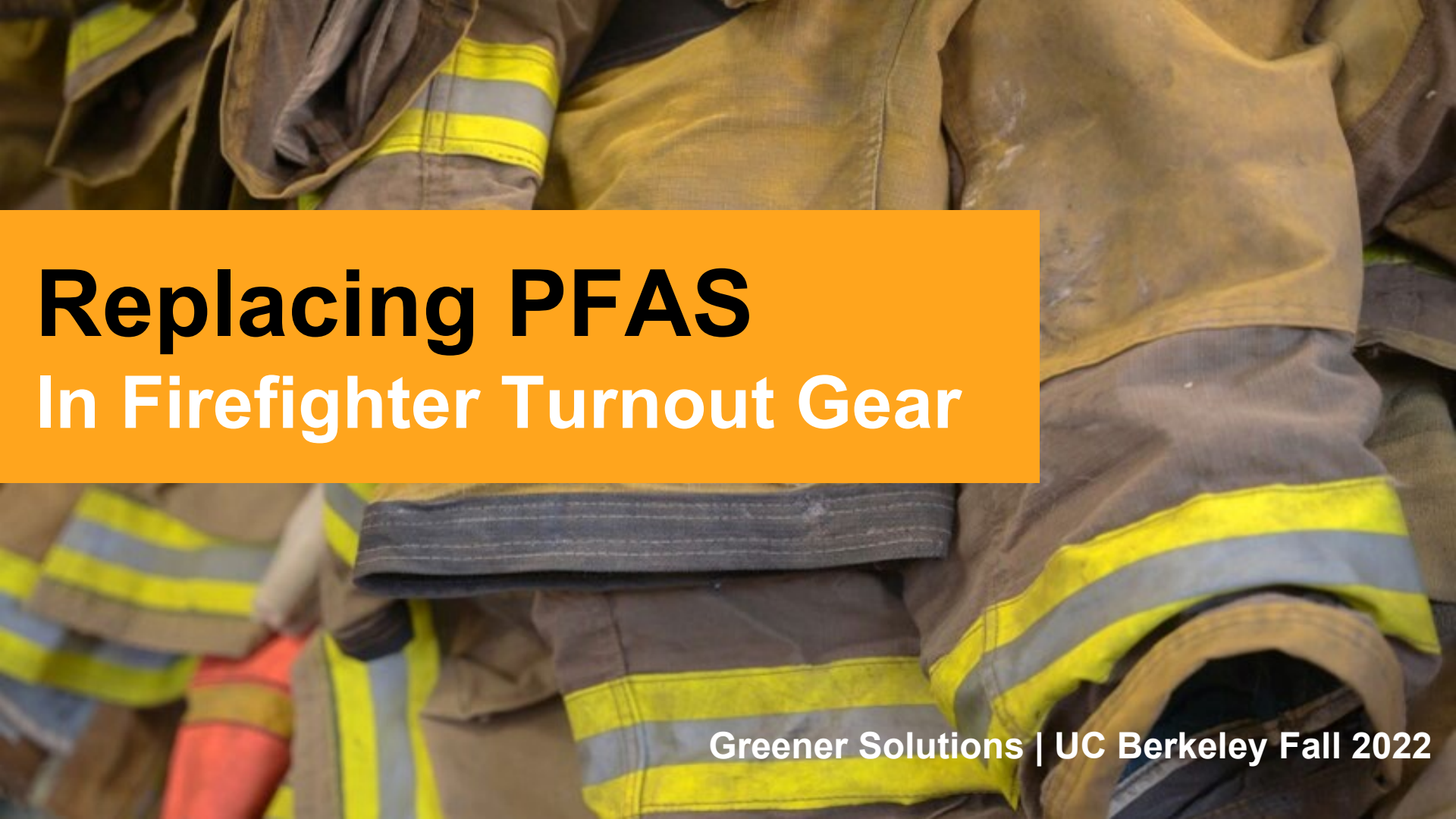

Replacing PFAS
In Firefighter Turnout Gear

Greener Solutions | UC Berkeley Fall 2022

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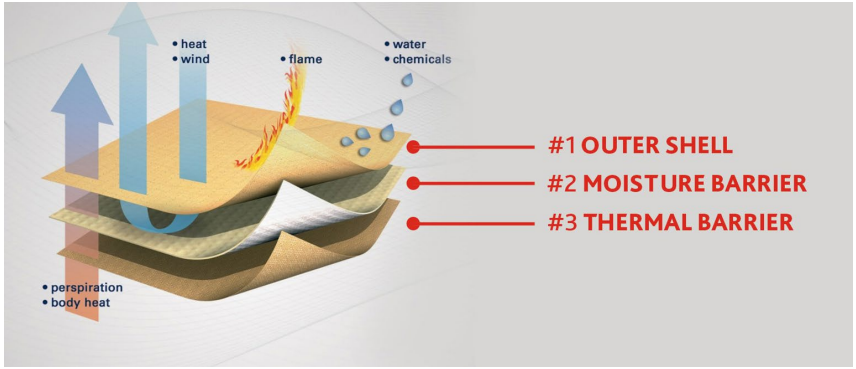
Challenge

Find safer alternative materials that meet the required functions of the PTFE moisture barrier in firefighter turnout gear

Current Turnout Gear

Typically **3** layers in firefighter turnout gear: **Thermal Layer, Moisture Barrier, Outer Shell**



(*Peeling Back the Fire Suit "Onion", Layer #2*, n.d.)

The **Moisture Barrier** contains a **Polytetrafluoroethylene (PTFE)** layer.

PTFE is …

- a synthetic fluoropolymer (a polymer with multiple fluorine carbon bonds)
- one of the most well-known and applied **per- and polyfluoroalkyl substances (PFAS)** - also used in the coating of non-stick cookware.

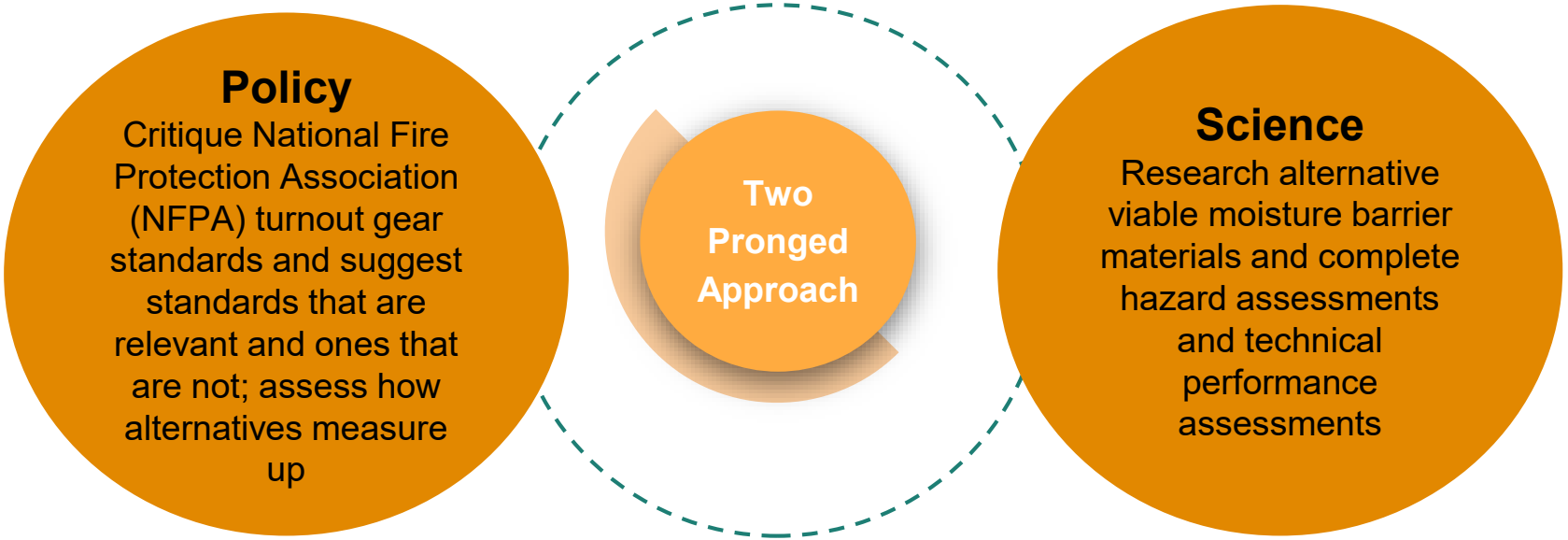
PFAS were detected in all three layers of the firefighter turnout gear. While **PTFE** is considered inert, smaller **PFAS chemicals present on firefighter turnout gear pose a risk to human and environment health.**
(Graham et al., 2020)

Why does this matter?

Firefighters are disproportionately burdened by cancer

- Firefighting as an occupational exposure is considered a **Class 1 carcinogen** (IARF WHO 2022)
- The **leading cause of death in the fire services** has gone from cardiac events to cancer (IAFF)
- NIOSH reports firefighters have a **9% higher risk** of cancer diagnosis and a **14% higher risk** of cancer-caused mortality than the total U.S. population (Daniels et. al., 2013).
- PFAS exposure has been **linked to multiple types of cancers**, including kidney and testicular cancer, among many other health effects (Goodrich et al., 2021)

Approach to Addressing Challenge

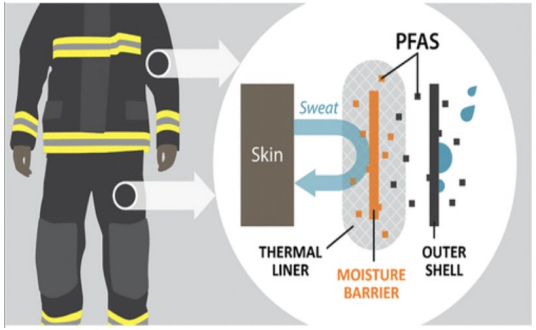


Comparison of Standards

Requirements	NFPA (US & Canada)	EN 469 - Level 2 – Structural fires (Europe)	AUS (Australia)
Heat/Thermal Resistance	Shall not shrink > **10%** in any direction.	Shall not shrink >**5%** in any direction. No ignition. No melting.	X
Water Penetration (resistance)	Minimum water penetration resistance of **172 kPa (25 psi)**.	Minimum water resistance of **20 kPa**	Using the rate of water pressure increase of 9.8 mbar/min and water temperature of 20 °C shall achieve ≥ 200 cm of H2O
Tear resistance	Tear strength of not less than **22 N** (5 lbf).	Tear strength of no less than **30 N**	Coated materials shall give a tear strength equal to or greater than **25 N**
Flame Resistance	Char length **<100 mm**. Afterflame<**2 seconds.**	X	X
Cleaning Shrinkage Resistance	Cannot shrink more than **5%**	Shall not shrink more than **3 %** (woven) Shall not shrink more than **5%** (non-woven)	At a temperature of (260 0 +5) °C, no material shall melt, drip, ignite or shrink more than **5 %**
Liquid Chemical Resistance	No liquid can penetrate any sample for **1 hour**	No penetration to innermost surface, index of repellency **> 80%**	Clothing shall give **> 80 %** run off with no penetration to the innermost surface
Viral Penetration Resistance	Shall allow no penetration of the Phi-X-174 bacteriophage for at least 1 hour.	X	X
Light Degradation Resistance	Water shall not appear on the surface of the specimen. *Garment is exposed to harsh light for 40 hours	X	X
Water Vapor Resistance	X	Must be less than or equal to **30 m^2Pa/W**	X

NFPA Standards Critique
Light Degradation Resistance: The UV Test

- **Unnecessary** for moisture barrier: the middle layer of turnout gear does not come into contact with UV light.
- PTFE is the **only material** that meets this requirement → Removing the UV test allows for PFAS-free moisture barriers.
- May 2021, a Tentative Interim Amendment was filed by IAFF to remove UV test from the standards but NFPA denied it and subsequent appeals



(Graham et. al., 2020)

*"The UV light degradation test for moisture barriers is **illogical, not supported by science**, stands as a hurdle to advancing the state of the art in firefighter PPE"*

- IAFF TIA Appeal

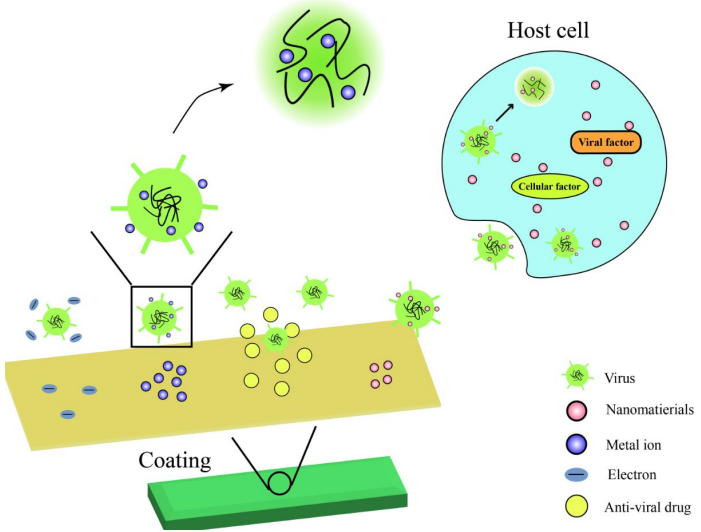
*"The UV light test is stopping fire departments from moving towards procurement of PPE that doesn't contain forever chemicals. **Firefighters should be fighting fires, not NFPA and the gear companies.**"*

- Retired battalion chief of New Haven CT Fire Department

(*Latest,* n.d.)

NFPA Standards Critique
Viral penetration resistance

- **Viral penetration test** – Resistance to liquid or bloodborne pathogens
- Unnecessary for moisture barrier – an inner layer – to meet this standard
- When firefighters act in an paramedic role, they have access to other PPE (gloves, masks, etc) that do meet viral penetration standards



(Pemmada, 2020)

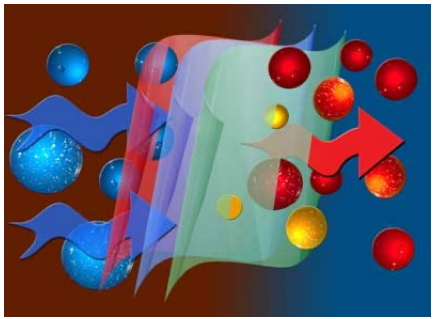
Technical Performance Standards

NFPA Standards:

- Heat/Thermal Resistance
- Water penetration (resistance)
- Tear resistance
- Liquid Chemical Resistance (Water contact angle)
- Flame Resistance
- Cleaning Shrinkage Resistance

Additional Standards:

- Water Vapor Permeability
- Water Vapor Resistance
- Pore Size



Step-wise Hazard Assessment

Hazard Ranking:

Categorical = **Very High**, **High**, **Medium**, **Low**, **Very Low**

GreenScreen Guidance Doc → European Chemicals Agency (ECHA) Dossier → Literature Search

Priority Hazards/Population of Concern: Group 1 Endpoints (especially Carcinogenicity) + Firefighters

Confidence Ranking:

High Confidence = Hazard level clearly ranked in GreenScreen

Medium Confidence = Extrapolation from a range from GreenScreen (e.g. given a range of **vH-M**, chose **H**), modeled or unverified value, or extrapolated from different GreenScreen ranking entities

Low Confidence = Values (e.g. NOAELs or LD50s) provided by ECHA and compared to known values from high hazard chemicals or ECHA hazard ranking from preliminary animal studies

Hazard Assessment

"Bad Actors"

		Group I Human Endpoints			Group II and Group II* Endpoints			Ecotoxicity	Fate	Physical Hazard
		Carcinogen./ Mutagen.	Develop./ Repro. Tox	Endocrine Activity	Systemic Toxicity	Neurotoxicity	Skin, Eye, Respiratory Irritation/ Sensitiz.	Aquatic Tox. Acute/ Chronic	Persistence /Bioaccumu.	Reactivity, flammability
PTFE + PTFE Monomer	PTFE	M	Data Gap	Data Gap	Data Gap	Data Gap	Data Gap	Data Gap	vH	Data Gap
	TFE	H	vH	Data Gap	H	H	M	Data Gap	vH	H
C8s/Legacy PFAS	PFOA	H	H	H	H	H	vH	M	vH	Data Gap
	PFOS	H	H	H	H	Data Gap	M	H	vH	Data Gap
C6s/Novel PFAS	GenX	Data Gap	vH	Data Gap	M	Data Gap	vH	Data Gap	vH	L
	PFDeA/PFDA	M	H	H	H	Data Gap	vH	Data Gap	vH	Data Gap
Brominated FR	TBBPA	H	H	H	Data Gap	Data Gap	Data Gap	vH	vH	Data Gap

Major Group 1 & 2 Endpoints

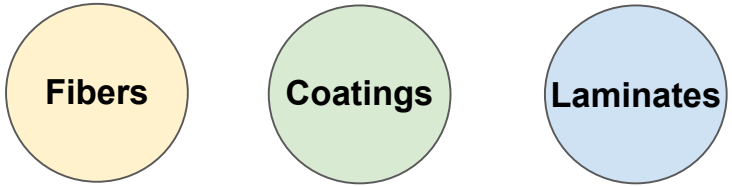
Extremely persistent

Components of the Moisture Barrier

GORE®PARALLON™ Liner System

GORE®PARALLON™ Liner System (3 Layers in this moisture barrier):

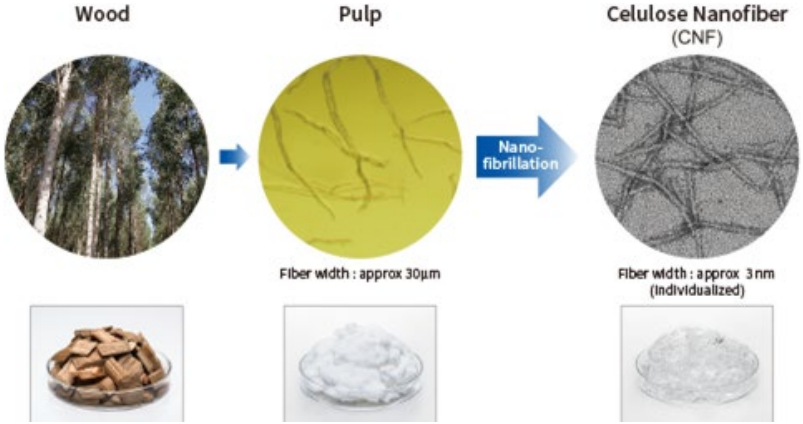
1. **Exterior Layer:** Nomex, flame resistant fabric, and a laminated ePTFE film
2. **Middle Layer:** KEVLAR/NOMEX blend and a laminated ePTFE film
3. **Body-Side layer:** KEVLAR/ NOMEX, LENZING fiber, and a laminated ePTFE film



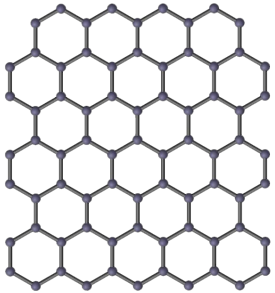
Fibers

Cellulose Fibers

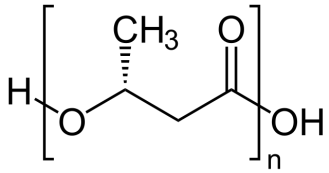
Cellulose nanofibers
Viscose Rayon
Cotton
Lyocell



Graphene



PHAs



Technical Performance
Fibers

	Compound	**Water Penetration Resistance**
Current Fabrics	*Kevlar (single layer)*	
	Kevlar/Wool Blend (single layer)	
	NOMEX	
Graphene	Graphene Nanofibers	
Cellulose Based Fabrics	Cellulose Nanofibers	
	Lyocell (Tencel)	
	Cotton	
	Viscose Rayon	
Biobased Fabric	PHA/PHB fibers	

NFPA: >172 kPa (25 PSI)

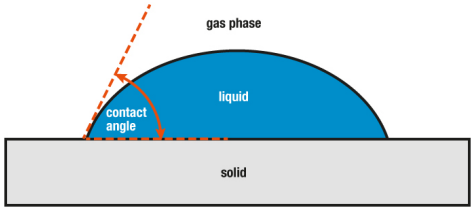
- Measures the amount of water pressure it takes to penetrate a certain distance into a fiber

Data Gap

Technical Performance
Fibers

	Compound	Water Penetration Resistance	Liquid Chemical Resistance *Water Contact Angle (degree)*
Current Fabrics	*Kevlar (single layer)*		61.2-66.2
	Kevlar/Wool Blend (single layer)		
	NOMEX		144.7
Graphene	Graphene Nanofibers		95-100
Cellulose Based Fabrics	Cellulose Nanofibers		85.9
	Lyocell (Tencel)		
	Cotton		43.9
	Viscose Rayon		
Biobased Fabric	PHA/PHB fibers		118

NFPA: No Liquid can penetrate for 1 hour



>100°

70°-100°

0°-69°

Technical Performance
Fibers

	Compound	Water Penetration Resistance	Liquid Chemical Resistance *Water Contact Angle (degree)*	Thermal Resistance *(m^2K/W)*
Current Fabrics	*Kevlar (single layer)*		61.2-66.2	0.008
	Kevlar/Wool Blend (single layer)			0.011
	NOMEX		144.7	
Graphene	Graphene Nanofibers		95-100	0.09 m K/W
Cellulose Based Fabrics	Cellulose Nanofibers		85.9	
	Lyocell (Tencel)			
	Cotton		43.9	0.01301 m K/W
	Viscose Rayon			0.189
Biobased Fabric	PHA/PHB fibers		118	

NFPA: Shall not shrink >10% in any direction

>0.008 m^2K/W

<0.008 m^2K/W

Technical Performance
Fibers

	Compound	Water Penetration Resistance	Liquid Chemical Resistance *Water Contact Angle (degree)*	Thermal Resistance (m^2*K/W)	Tear Resistance (Newtons)
Current Fabrics	*Kevlar (single layer)*		61.2-66.2	0.008	3620 N/mm
	Kevlar/Wool Blend (single layer)			0.011	
	NOMEX		144.7		113
Graphene	Graphene Nanofibers		95-100	0.09 m K/W	
Cellulose Based Fabrics	Cellulose Nanofibers		85.9		
	Lyocell (Tencel)				21.7168
	Cotton		43.9	0.01301 m K/W	22.78
	Viscose Rayon			0.189	
Biobased Fabric	PHA/PHB fibers		118		40 N/mm

NFPA: >22N

>22N

<22N

Hazard Assessment
Fibers

	Group I Human Endpoints			Group II and Group II* Endpoints			Ecotoxicity	Fate	Physical Hazard
	Carcinogen. /Mutagen.	Develop./ Repro. Tox	Endocrine Activity	Systemic Toxicity	Neurotoxicity	Skin, Eye, Respiratory Irritation/ Sensitiz.	Aquatic Tox. Acute/ Chronic	Persistence /Bioaccumu.	Reactivity, flammability
Cellulose (Viscose Rayon, Lyocell, Cotton, Cellulose Nanofibers)	Data Gap	Data Gap	Data Gap	Data Gap	Data Gap	H	Data Gap	Data Gap	Data Gap

Respiratory Sensitization (relevant to manufacturer exposure)

Hazard Assessment
Fibers

	Group I Human Endpoints			Group II and Group II* Endpoints			Ecotoxicity	Fate	Physical Hazard
	Carcinogen./ Mutagen.	Develop./ Repro. Tox	Endocrine Activity	Systemic Toxicity	Neurotoxicity	Skin, Eye, Respiratory Irritation/ Sensitiz.	Aquatic Tox. Acute/ Chronic	Persistence /Bioaccumu.	Reactivity, flammability
Cellulose (Viscose Rayon, Lyocell, Cotton, Cellulose Nanofibers)	Data Gap	Data Gap	Data Gap	Data Gap	Data Gap	H	Data Gap	Data Gap	Data Gap
Short chain PHA Monomers	L	Data Gap	Data Gap	Data Gap	Data Gap	Data Gap	L	vL	Data Gap

Biodegradable Polymer → Very Low Persistence and Bioaccumulation

Hazard Assessment
Fibers

	Group I Human Endpoints			Group II and Group II* Endpoints			Ecotoxicity	Fate	Physical Hazard
	Carcinogen./ Mutagen.	Develop./ Repro. Tox	Endocrine Activity	Systemic Toxicity	Neurotoxicity	Skin, Eye, Respiratory Irritation/ Sensitiz.	Aquatic Tox. Acute/ Chronic	Persistence /Bioaccumu.	Reactivity, flammability
Cellulose (Viscose Rayon, Lyocell, Cotton, Cellulose Nanofibers)	Data Gap	Data Gap	Data Gap	Data Gap	Data Gap	H	Data Gap	Data Gap	Data Gap
Short chain PHAs Monomers	L	Data Gap	Data Gap	Data Gap	Data Gap	Data Gap	L	vL	Data Gap
Graphene Monomers	L	Data Gap	Data Gap	L	Data Gap	L	M	H	L

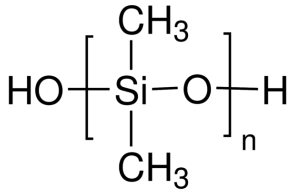
Color Scale: Lighter Color = Less Certainty!

Persistent

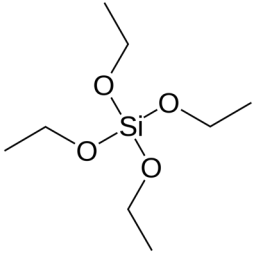
Potentially related to persistence

Coatings

Silicon Flame Retardants

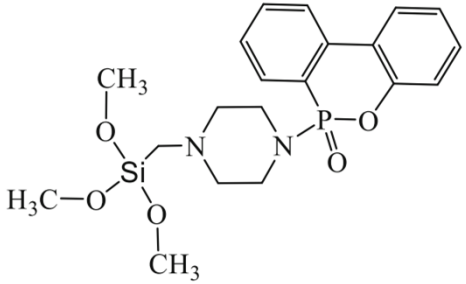


HPDMS

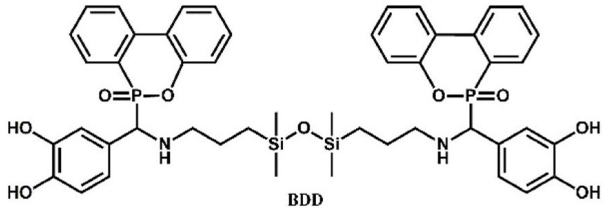


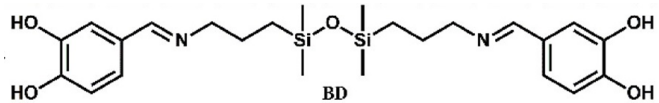
TEOS

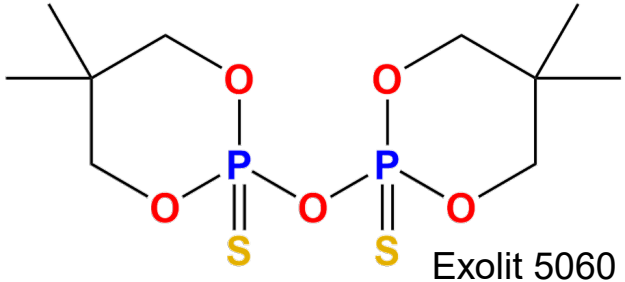
Phosphorus Flame Retardants



DOPO-PiP-Si

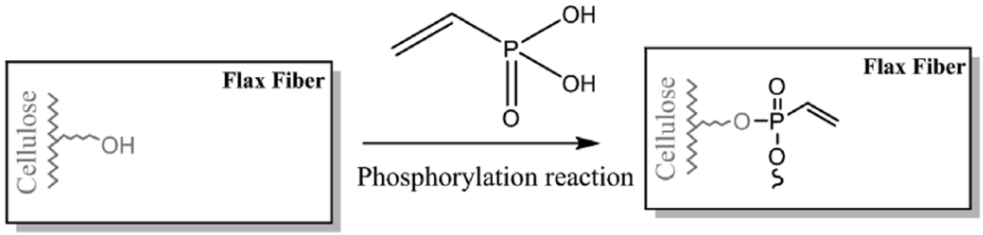






Exolit 5060 PK

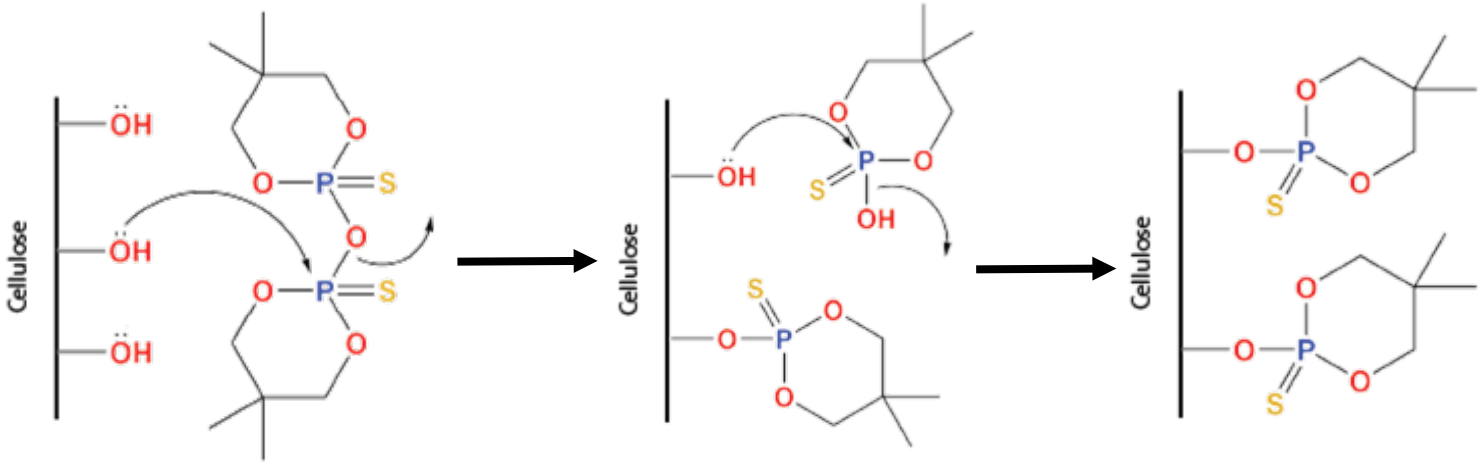
Flame Retardant Coatings are incorporated into fibers



Flame Retardant coatings are incorporated into fibers by reacting with the functional groups on the fiber.

1. **Decreases flammability of the fiber**
2. **Potentially decreases reactivity enabling it to act as a moisture barrier**

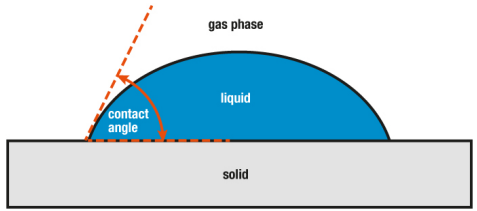
Fire Retardant Coatings are incorporated into fibers in two processes



Technical Performance
Fibers + Coatings

	Compound	Liquid Chemical Resistance Water Contact Angle (degree)
Phosphorus Based Flame Retardants	Viscose Rayon + Exolit 5060 PK	**Stable in Acidic and Basic Solution**
	Cotton + DOPO	
Silicon Based Flame Retardants	Cotton + BD	
	Cotton + BDD	
	Cotton + TEOS/HPDMS	>160

NFPA: No Liquid can penetrate for 1 hour



>100°

70°-100°

0°-69°

Technical Performance
Fibers + Coatings

	Compound	Liquid Chemical Resistance Water Contact Angle (degree)	Thermal Decomposition (5%) Temperature (℃)
Phosphorus Based Flame Retardants	Viscose Rayon + Exolit 5060 PK	**Stable in Acidic and Basic Solution**	
	Cotton + DOPO		220
Silicon Based Flame Retardants	Cotton + BD		162
	Cotton + BDD		225
	Cotton + TEOS/HPDMS	>160	264

Technical Performance
Fibers + Coatings

	Compound	Liquid Chemical Resistance Water Contact Angle (degree)	Thermal Decomposition (5%) Temperature (℃)	Char Length (cm)*
Phosphorus Based Flame Retardants	Viscose Rayon + Exolit 5060 PK	**Stable in Acidic and Basic Solution**		
	Cotton + DOPO		220	12.2*
Silicon Based Flame Retardants	Cotton + BD		162	
	Cotton + BDD		225	
	Cotton + TEOS/HPDMS	>160	264	8.5*

Hazard Assessment

Coatings

	Group I Human Endpoints			Group II and Group II* Endpoints			Ecotoxicity	Fate	Physical Hazard
	Carcinogen./ Mutagen.	Develop./ Repro. Tox	Endocrine Activity	Systemic Toxicity	Neurotoxicity	Skin/Eye/ Respirat Irrit./ Sensitiz.	Aquatic Tox. Acute/ Chronic	Persistence /Bioaccumu.	Reactivity, flammability
Silicon Based Flame Retardants	Data Gap	Data Gap	Data Gap	Data Gap	Data Gap	H	Data Gap	Data Gap	Data Gap
Used to make BD & BDD	L	Data Gap	Data Gap	L	Data Gap	M	L	L	Data Gap
	Data Gap	Data Gap	Data Gap	Data Gap	Data Gap	vH	vH	Data Gap	Data Gap
TEOS	Data Gap	L	Data Gap	vH	Data Gap	H	Data Gap	L	M
HPDMS	Data Gap	Data Gap	Data Gap	Data Gap	Data Gap	H	Data Gap	L	Data Gap

Few Group 1 Endpoints

Related to Respiratory Irritation

Skin and Eye Irritation (less risk to firefighters)

Hazard Assessment

Coatings

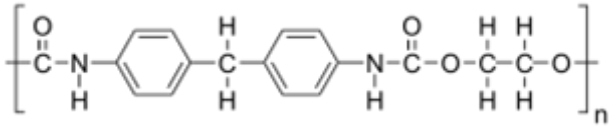
		Group I Human Endpoints			Group II and Group II* Endpoints			Ecotoxicity	Fate	Physical Hazard
		Carcinogen./ Mutagen.	Develop./ Repro. Tox	Endocrine Activity	Systemic Toxicity	Neurotoxicity	Skin/Eye/ Respirat Irrit./ Sensitiz.	Aquatic Tox. Acute/ Chronic	Persistence /Bioaccumu.	Reactivity, flammability
Silicon Flame Retardants		Data Gap	Data Gap	Data Gap	Data Gap	Data Gap	H	Data Gap	Data Gap	Data Gap
		L	Data Gap	Data Gap	L	Data Gap	M	L	L	Data Gap
		Data Gap	Data Gap	Data Gap	Data Gap	Data Gap	vH	vH	Data Gap	Data Gap
		Data Gap	L	Data Gap	vH	Data Gap	H	Data Gap	L	M
		Data Gap	Data Gap	Data Gap	Data Gap	Data Gap	H	Data Gap	L	Data Gap
Phosphorus Based Flame Retardants	Exolit 5060 PK	Data Gap	L	Data Gap	L	H	L	M	M	L
	DOPO (Novel Phosphorus FR)	Data Gap	Data Gap	Data Gap	Data Gap	Data Gap	H	H	Data Gap	Data Gap
	Two phosphorus based pesticides	Data Gap	H	H	vH	H	H	vH	vH	Data Gap
		H	M	H	H	H	H	vH	vH	Data Gap

Data gaps for Novel Phosphorus FRs

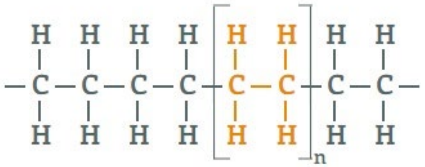
Major Group 1 & 2 Endpoints for phosphorus based pesticides = worst case health scenario

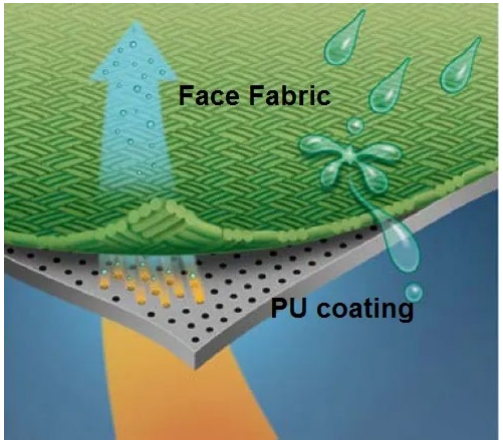
Laminates

Polyurethane



Polyethylene





Technical Performance
Laminates

Compound	Water Penetration Resistance	Liquid Chemical Resistance Water Contact Angle (degree)	Thermal Resistance (m^2C/W)	Tear Resistance (Newtons)
ePTFE		125.5	0.0671	
Polyurethane	1.0*10^-3-1.0*10^-4 (g/mdayPa)	70	0.0659	
ePolyethylene		126		33.32

NFPA
>172 kPa (25 PSI)

	>100°		>0.008 m^2K/W		>22N
	70°-100°		<0.1 mK/W		<22N
	0°-69°		<0.008 m^2K/W		

Hazards Assessment
Laminates

	Group I Human Endpoints			Group II and Group II* Endpoints			Ecotoxicity	Fate	Physical Hazard
	Carcinogen./ Mutagen.	Develop./ Repro. Tox	Endocrine Activity	Systemic Toxicity	Neurotoxicity	Skin, Eye, Respiratory Irritation/ Sensitiz.	Aquatic Tox. Acute/ Chronic	Persistence /Bioaccumu.	Reactivity, flammability
Polyethylene	L	Data Gap	Data Gap	Data Gap	Data Gap	M	Data Gap	vH	Data Gap
Polyethylene Monomer	M	L	Data Gap	M	H	Data Gap	M	Data Gap	H

Potential Group 1 Endpoints

Neurotoxicity

Persistent synthetic polymer

Hazards Assessment
Laminates

	Group I Human Endpoints			Group II and Group II* Endpoints			Ecotoxicity	Fate	Physical Hazard
	Carcinogen./ Mutagen.	Develop./ Repro. Tox	Endocrine Activity	Systemic Toxicity	Neurotoxicity	Skin, Eye, Respiratory Irritation/ Sensitiz.	Aquatic Tox. Acute/ Chronic	Persistence /Bioaccumu.	Reactivity, flammability
Polyethylene	L	Data Gap	Data Gap	Data Gap	Data Gap	M	Data Gap	vH	Data Gap
Polyethylene Monomer	M	L	Data Gap	M	H	Data Gap	M	Data Gap	H
Polyurethane	L	Data Gap	Data Gap	Data Gap	Data Gap	H	Data Gap	Data Gap	Data Gap
Polyurethane Monomers	M	M	Data Gap	H	Data Gap	H	Data Gap	Data Gap	Data Gap
	L	M	Data Gap	M	Data Gap	H	L	Data Gap	Data Gap

Potential Group 1 Endpoints

Associated with respiratory system → Not major firefighter risk

Skin and Respiratory Sensitization

Additional Performance Metrics
Fibers + Laminates

	Compound	Pore Size (diameter, μm)
Existing Fabric	*Kevlar (single layer)*	9.0-12.8
	Kevlar/Wool Blend (single layer)	
	NOMEX	10-100
Graphene	Graphene Nanofibers	0.003-0.050
Cellulose Based Fibers	Cellulose Nanofibers	0.02-0.3
	Lyocell	0.001-0.1
	Cotton	
Existing Laminate	*ePTFE*	0.02-10
Alternative Laminate	Polyurethane	677
	Polyethylene	1-50

Pore Size: Distance between two sides of a pore

- >0.004 and <1
- >1 and <100
- >100

Water Vapor (0.0004μm)
Liquid Water (1-100μm)

Additional Performance Metrics
Fibers + Laminates

	Compound	Pore Size (diameter, μm)	Water Vapor Transmission Rate (g/(m²day))
Existing Fabric	*Kevlar (single layer)*	9.0-12.8	1815.67
	Kevlar/Wool Blend (single layer)		
	NOMEX	10-100	1967.13-2151.01
Graphene	Graphene Nanofibers	0.003-0.050	848.22
Cellulose Based Fibers	Cellulose Nanofibers	0.02-0.3	2.46 (g/(m*s*Pa)*10^-11))
	Lyocell	0.001-0.1	~1000
	Cotton		1912.36
Existing Laminate	*ePTFE*	0.02-10	5000-8000
Alternative Laminate	Polyurethane	677	~1180-1500, 3960-4600
	Polyethylene	1-50	1.54

Water Vapor Transmission Rate: The rate at which water vapor passes through a fiber or membrane at a certain humidity.

- >1500
- 750-1500
- <1500

Additional Performance Metrics
Fibers + Laminates

	Compound	Pore Size (diameter, μm)	Water Vapor Transmission Rate (g/(m²day))	Water Vapor Resistance (m²Pa/W)
Existing Fabric	*Kevlar (single layer)*	9.0-12.8	1815.67	9.2
	Kevlar/Wool Blend (single layer)			7.3
	NOMEX	10-100	1967.13-2151.01	2.448-2.836
Graphene	Graphene Nanofibers	0.003-0.050	848.22	
Cellulose Based Fibers	Cellulose Nanofibers	0.02-0.3	2.46 (g/(m*s*Pa)*10^-11))	
	Lyocell	0.001-0.1	~1000	4.42
	Cotton		1912.36	3.305
Existing Laminate	*ePTFE*	0.02-10	5000-8000	
Alternative Laminate	Polyurethane	677	~1180-1500, 3960-4600	
	Polyethylene	1-50	1.54	

EN (Europe)
<30 **m²Pa/W**

<30

>30

Conclusions and Recommendations
Technical Assessment

Fibers

Cellulose Fibers

Meets Tears Resistance
Low Water Contact angle

Short Chain PHAs

High Water Contact Angle
Data Gaps

Graphene

Low Water Contact Angle
Low Thermal Resistance

Coatings

Silicon Based Flame Retardants

Increase Water Contact Angle
Data Gaps

Phosphorus Based Flame Retardants

Increase Thermal Decomposition Temperature
Data Gaps

Laminates

Polyethylene

High Water Contact Angle
Data Gaps on Thermal Resistance

Polyurethane

Low Water Contact Angle
Meets other standards

Conclusions and Recommendations
Hazard Assessment

Fibers

Cellulose Fibers

Manufacturing Risk
Data Gaps

Short Chain PHAs

Biodegradable
Data Gaps

Graphene

Concerns of Persistence
Data Gaps

Coatings

Silicon Based Flame Retardants

Few Group 1 Endpoints
Potential Manufacturer Risk

Phosphorus Based Flame Retardants

Many Group 1 Endpoints
Data Gaps for Novel PFRs

Laminates

Polyethylene

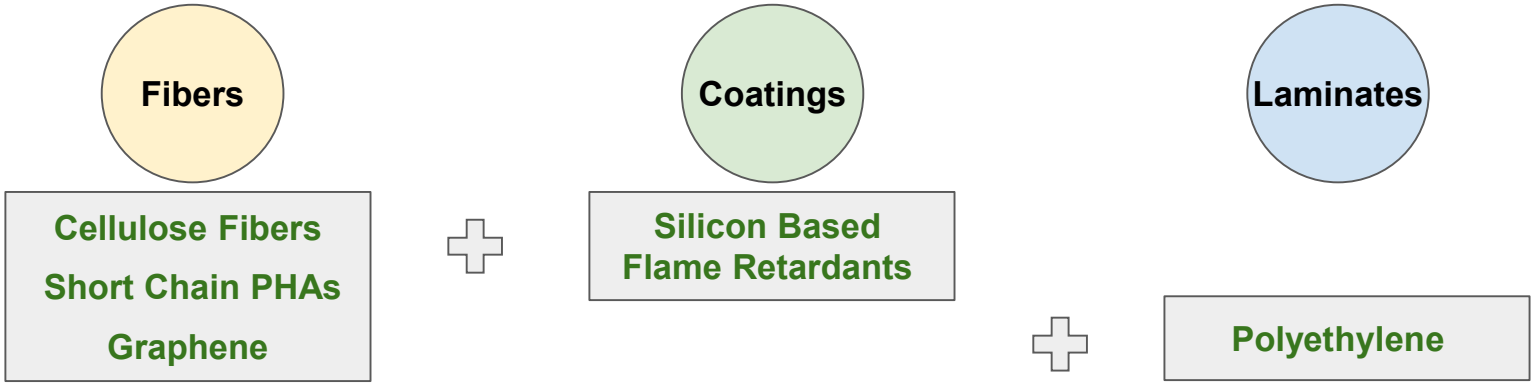
Monomer Potential Carcinogen
Polymer Persistence

Polyurethane

Monomer Potential Carcinogen
Potential Manufacturer Risk

Conclusions and Recommendations

Science Recommendations



Policy Recommendations

- We advise the NFPA to *drop the light degradation and viral penetration tests* and keep those that remain.
  - Light degradation & viral penetration tests result in over-engineered moisture barrier
  - Standards are limiting viable PFAS-free options

Remaining Questions

- We evaluated each of our science strategies (fabrics, fabrics/coatings, laminates) separately, but would combining all three of these produce a better moisture barrier, enhance moisture barrier properties?
- Although phosphorus and silicon based flame retardants could be used in the moisture barrier, they could pose other health hazards to firefighters; data gaps
- How do we balance the health hazards and technical performance in our assessment of the viability of these alternatives?
- Although data gaps exist, our three strategies offer novel suggestions that advance the field of occupational firefighter health

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