Summary Report on Development of Holistic Assessment for Firefighter Protective Hood

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Aims: In response to the introduction of particulate-blocking firefighter hoods, the Textile Protection and Comfort Center (TPACC) at NC State University aimed to enhance the safety of firefighters by developing a system-level methodology for evaluating protective hood materials and designs for trade-offs between protection (particulate and flashfire), comfort, durability, and situation awareness.

Rationale for Study: Prior to 2016, protective hood variations were mainly based on different designs, bib lengths, fiber types and blends, and whether they were a traditional two-layer knit hood or a three-layer option designed for instructors. Particulate-blocking hoods were first introduced as a direct response to the heightened awareness of carcinogenic soot deposition on the head, face, and neck of firefighters brought to the forefront by a 2015 fluorescent aerosol test conducted on a traditional knit hood. The clearly visible deposition of particulate on the neck of the test subject alarmed the fire service to the potential weakness in their protective gear. The rationale of this research project was to further the understanding of this vulnerability and the performance trade-offs between traditional hoods and the new particulate-blocking alternatives.

Relevance to the Fire Service: The chief concern of this research was providing firefighters with an unbiased assessment of the utility of particulate-blocking hoods compared to traditional hoods so that they could determine within their own departments if these new pieces of equipment could better protect them from smoke exposures without negatively impacting their ability to do their jobs effectively.

Methods: Material-level performance of thermal protection (TPP), particulate protection, total heat loss (THL), mechanical strength, moisture absorption, and air permeability were conducted according to NFPA 1971 prescribed methods, where applicable. For hood-level evaluations, the PyroHead™ flash fire manikin and the thermal sweating head form testing platforms were further optimized and compared to their corresponding material-level assessments. The fluorescent aerosol test was used with multiple static head forms to evaluate the particulate-blocking abilities of different hood designs at different wind speeds. To assess the durability of hood materials, simulated on-the-job stressors were used including 100 washes with 200 don/doff cycles and accelerated exposures to sunlight. The final phase of the research involved field assessments with firefighters in live-fire at training centers where the laboratory data was compared to field data.

Outcomes: The most important finding in this research was that the construction and design of the protective hoods have more of an impact on the performance than any of the individual materials that are used. As shown in Fig. 1, the current market of hoods revolves around three particulate-blocking technologies (filtration or membrane-based) and constructions as either 2 or 3-layered versions. The relationships between NFPA 1971 material-level assessments of hood composites (Figs. 2-5) show that to have complete particulate protection firefighters do not necessarily have to sacrifice thermal protection, comfort, or situation awareness depending on the layering of the materials. As shown from hood-level testing (Figs. 6-12), 2-layer particulate-blocking hoods can provide comparable flashfire protection (especially when worn with the full head ensemble) to traditional hoods while also allowing for similar thermal comfort and ability to feel heat on the fire scene. Hood-level testing of both particulate-blocking and traditional hoods (Figs. 13-14) in the fluorescent aerosol test showed that particulate-blocking hoods can provide a 10x increase in protection compared to traditional hoods if doffing procedures are followed minimize contamination transfer. A smoke outward leakage headform demonstration and the Quantified Smoke Inspection Method (QSIM) were developed to help firefighters inspect their own hoods after use to determine if they are still blocking particulates (Figs. 15-16). The QSIM was adopted into the NFPA 1851 in the 2020 revision. Regardless of material, all of the hoods exhibited decreases in mechanical burst strength following extended sunlight exposure (Fig. 17), but the thermal protection and particulate-blocking were not impacted. The mechanical strength of the hoods was not significantly impacted following the laundering/donning/doffing cycles. Multiple manuscripts are also in publication and will be provided following their final publication.

Significance, Implication and Recommendations for Fire Service: All the currently NFPA 1971-certified particulate-blocking hoods provide significantly enhanced particulate protection compared to traditional knit hoods and do not necessarily require sacrificing in the other performance areas. The selection of hood should depend on fire department preferences such as fit, department tactics, and cost, with the most important element being the appropriate fit for everyone. The 2-layer particulate-blocking hoods can provide comparable thermal protection and comfort to traditional hoods and may be optimized for most firefighters. The 3-layer hoods provide much higher thermal protection with a trade-off of thermal comfort and situation awareness but may be needed if a department requires increased thermal protection or as instructor hoods. Hoods, as with the rest of the turnout ensemble, should be kept out of prolonged sunlight exposure as this will weaken the mechanical strength of the knit materials and could result in damage during normal wearing.

Figure 1: Main Types of Construction for Currently Available Protective Hoods

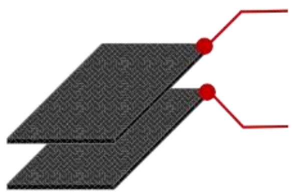
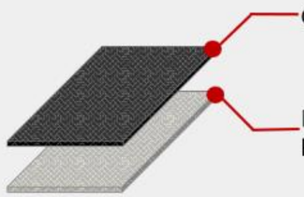
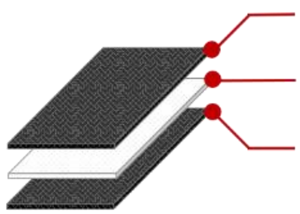
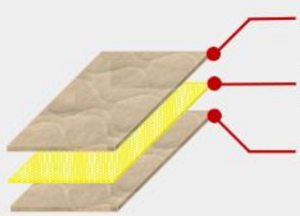
Hood Type	Construction	Materials
Traditional Hood 	 Outer Knit Layer Inner Knit Layer	100% Meta-aramid Meta-aramid/ FR Rayon Blend PBI/FR Rayon Blend Oxidized PAN Blend Other fiber blends
2-Layer Particulate Hood 	 Outer Knit Layer Inner Membrane-Based Particulate-Blocking Layer	Outer Side: Same as traditional hood Inner/Skin Side: PTFE-based membrane
3-Layer Particulate Hood 	 Outer Knit Layer Inner Membrane-Based Particulate-Blocking Layer Inner Knit Layer	Outer Side: Same as traditional hood Middle: PTFE-based membrane Inner/Skin Side: Same as traditional hood
3-Layer Particulate Hood 	 Outer Knit Layer Inner Nonwoven Filtration Particulate-Blocking Layer Inner Knit Layer	Outer: Same as traditional hood Middle: Nonwoven air permeable filtration layer Inner/Skin Side: Same as traditional hood

Figure 2: Effect of Particulate-Blocking Layer and Construction of Hood on Thermal Protective Performance (TPP) – Material-Level[1,2,3,4]

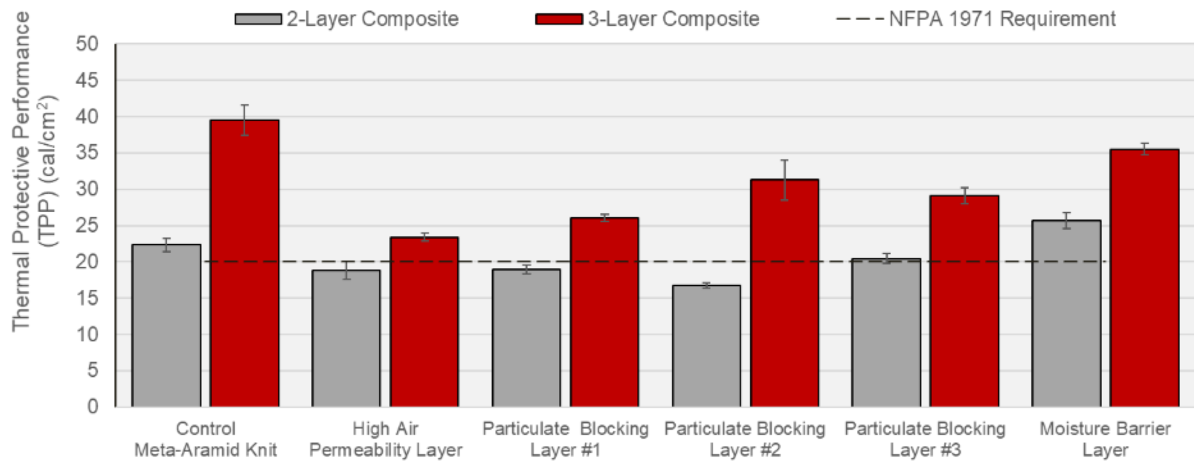
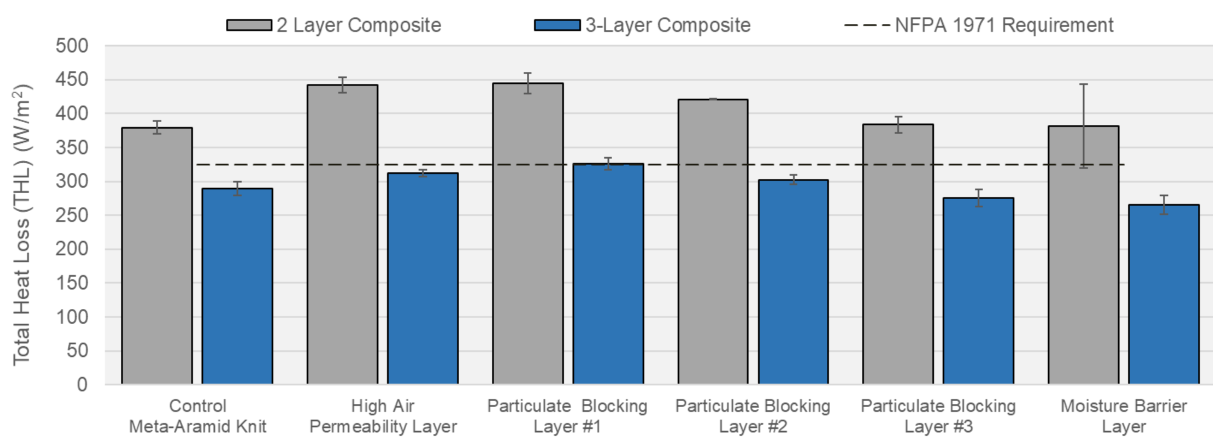


Figure 3: Effect of Particulate-Blocking Layer and Construction of Hood on Total Heat Loss (THL) – Material-Level[1,2,3,4]

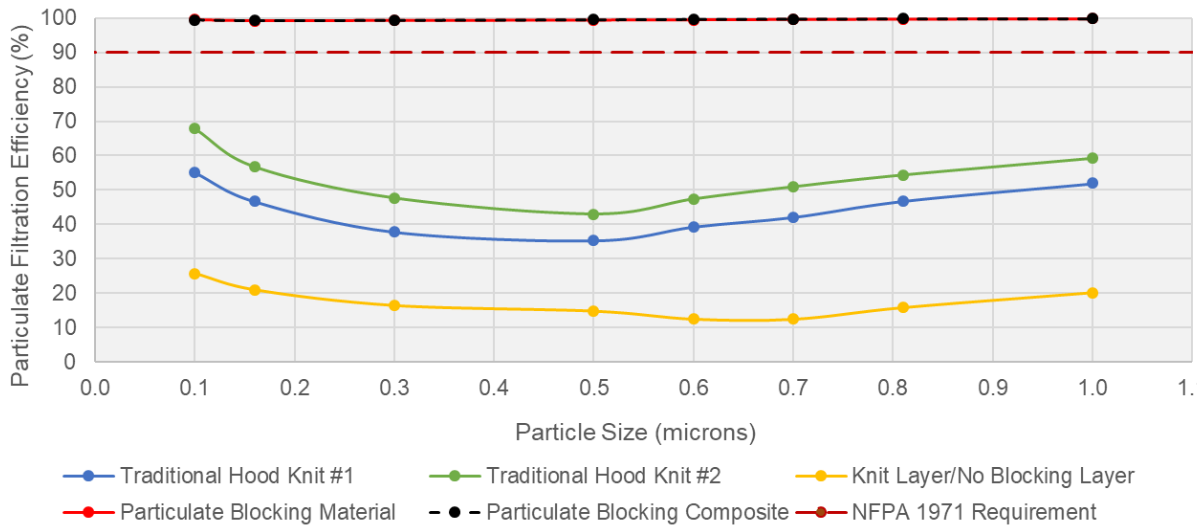


Main takeaways from the graphs:

- Hood construction (number of layers) is the main contributing factor to difference in TPP or THL
- Air permeability does not significantly affect either the measured TPP or THL values
- Main comparison should be between the 2-layer traditional (control) and either the 2-layer or 3-layer particulate-blocking composites as those are representative of the market
- The 2-layer construction with the knit outer and particulate-blocking layer inner has an optimized performance from the material-level evaluations – i.e. it has roughly the same TPP as the 2-layer traditional hood but slightly increased THL
- For more aggressive fire suppression tactics or instructors, a 3-layer hood may be more appropriate

[1] None of the samples for TPP were laundered prior to testing which is known to slightly increase the TPP values
[2] All composites consisted of 100% meta-aramid knit with the various particulate-blocking layers
[3] Higher TPP values indicate increased thermal protection and higher THL values indicate increased thermal comfort
[4] Samples are arranged in decreasing air permeability after the control composite

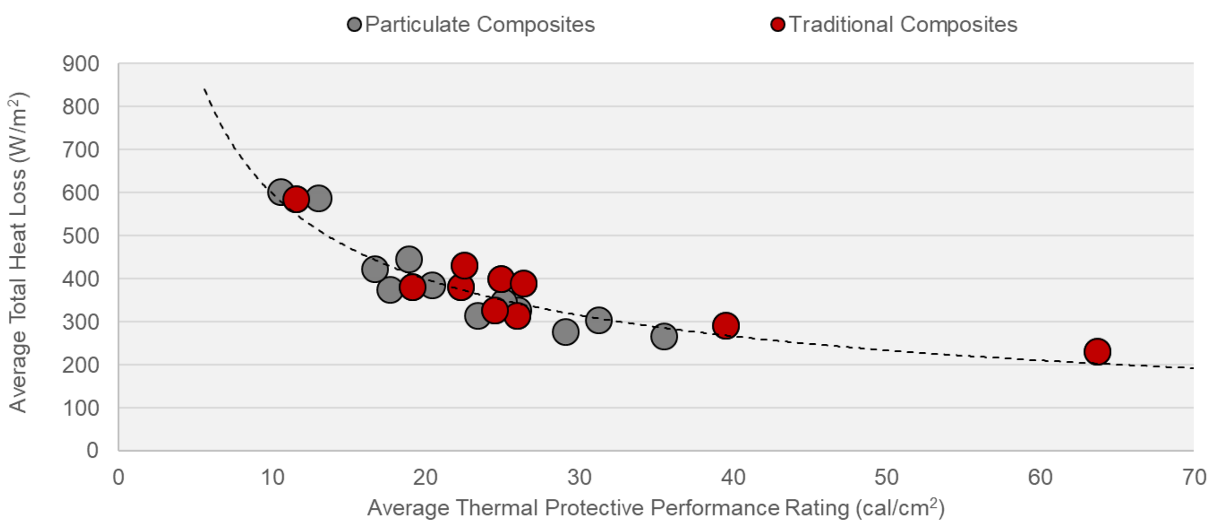
Figure 4: Particulate-Blocking Efficiency (PBE) of Traditional and Particulate-Blocking Hood Composites



Main takeaways from graph:

- Traditional 2-layer knit composites can provide between 35%-70% particulate-blocking efficiency across the relevant particle sizes that are common in structural fire smoke
- All NFPA 1971-certified particulate-blocking layers block more than 90% of particles

Figure 5: Relationship Between Thermal Protective Performance (TPP), Total Heat Loss (THL), and Particulate-Blocking Efficiency (PBE)[5]



Main takeaways from graph:

- The common balance between thermal protection and thermal comfort exists with both traditional and particulate-blocking hoods
- Particulate-blocking efficiency (~100%) does not significantly impact either the thermal protection or thermal comfort on its own, as the layered construction affects those performance metrics more
- Firefighters do not have to sacrifice thermal comfort or protection to have particulate protection

[5] All particulate-blocking composites blocked 100% of particles in the material-level assessment

Figure 6: System-Level PyroHead™ Flashfire Test Manikin

Note: By scanning the QR code above, you will be able to view a video of a 12-second flashfire exposure on the PyroHead™

Figure 7: Comparison of Damage Following Flashfire Exposure in Different Configurations

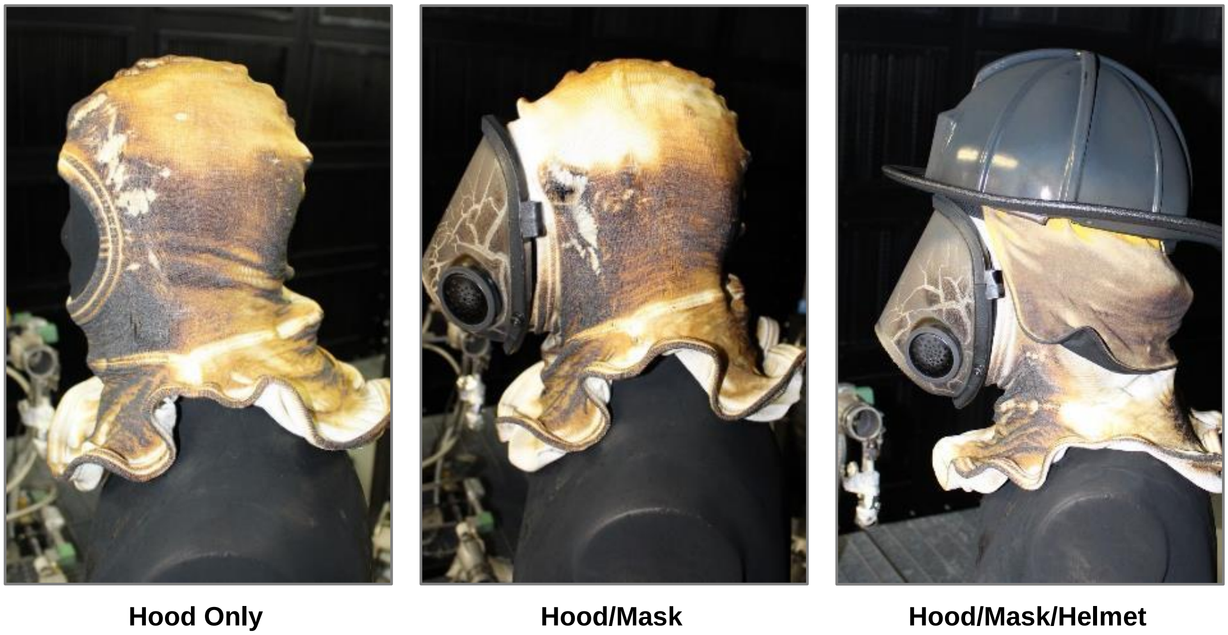
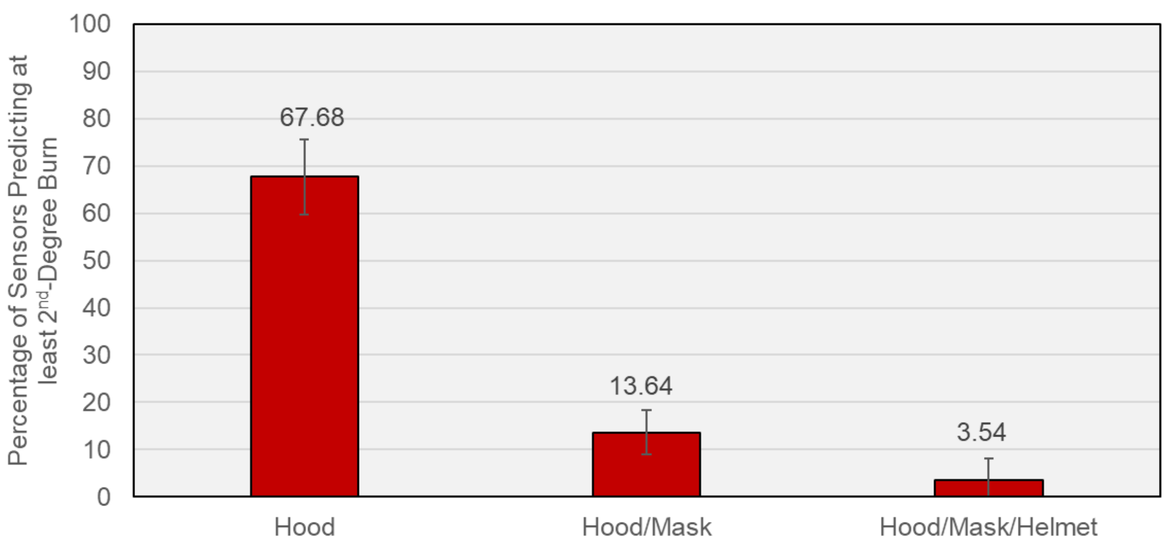


Figure 8: Comparison of Thermal Flashfire Protection on PyroHead™ with Different Configurations[6,7]



Main takeaways from graph:

- The full head ensemble consisting of the hood, mask, helmet, and ear flaps provides significant thermal protection in addition to the hood itself
- Additional thermal protection from a particulate-blocking hood is not necessarily needed

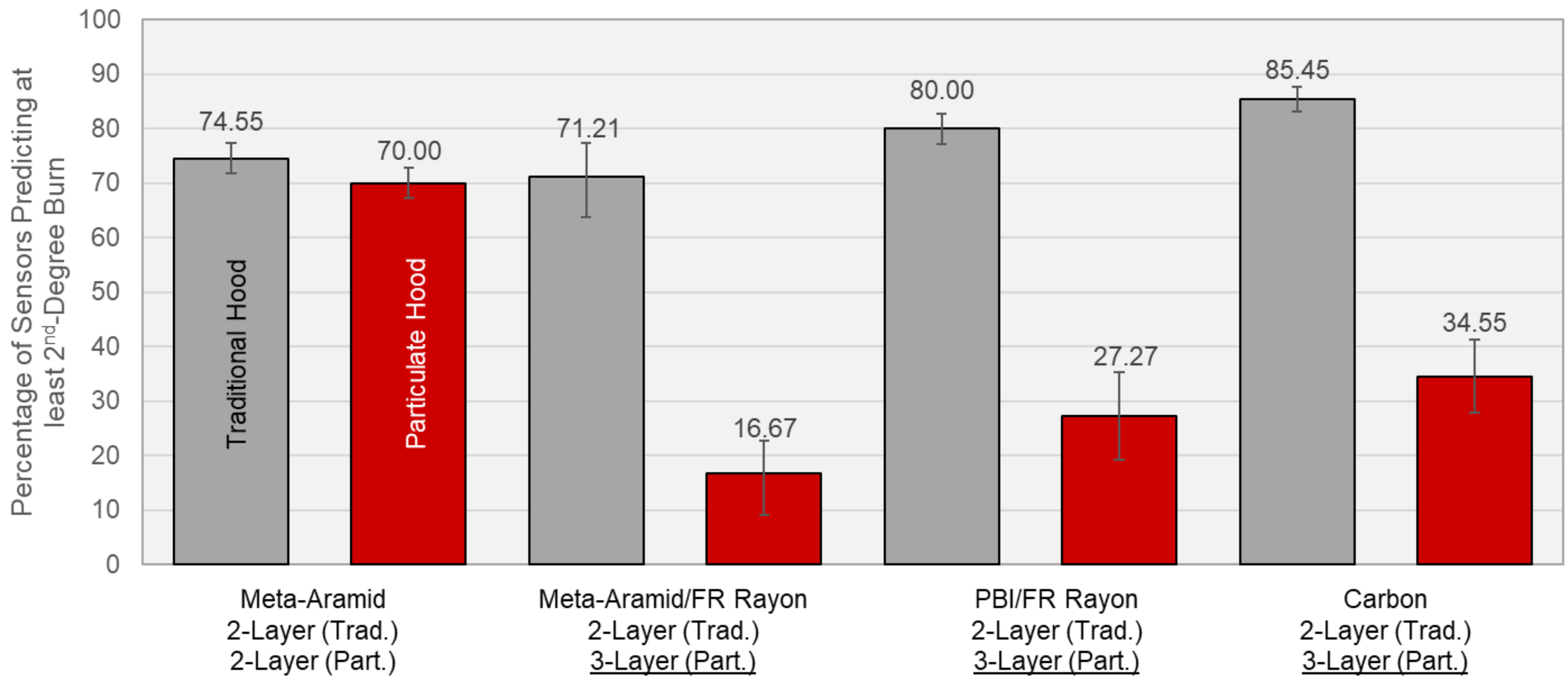
[6] The hood that was tested was a traditional 100% meta-aramid 2-layer knit
[7] The flashfire exposure was for seven seconds and each bar represents nine replicate burns over three days of testing

Figure 9: Comparison of Thermal Flashfire Protection When Full Head Ensemble is Worn

Traditional Hood - 100% meta-aramid
7-second flashfire exposure
Hood-only configuration

Traditional Hood - 100% meta-aramid
12-second flashfire exposure
Full head ensemble configuration
(hood, mask, helmet, ear flaps, jacket)

Figure 10: Comparison of Traditional and Particulate-Blocking Hoods on PyroHead™[8,9]



Main takeaways from the graph:

- The 2-layer particulate-blocking hood provided approximately the same level of thermal flashfire protection as currently experienced with the traditional hood.
- As expected, the 3-layer hoods provided significantly enhanced thermal protection on the head form test as they trap more air to insulate between the additional layers.
- With the full head ensemble worn, it is likely that all of the hoods would result in negligible predicted burn injuries.

[8] All hoods were exposed to a 7-second flashfire on PyroHead™ in the hood only configuration to evaluated only the protection provided by the hood
[9] All hoods were commercially-available, and the particulate-blocking hoods represented the counterpart to the traditional hoods being made of the same materials from the same manufacturer

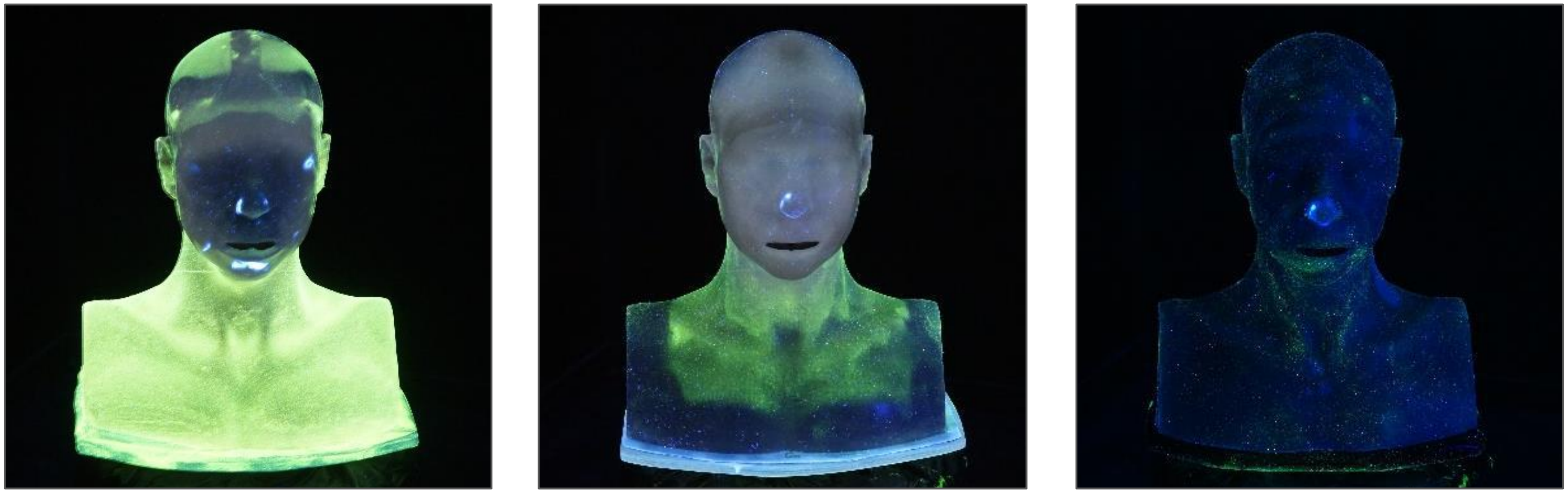
Figure 11: System-Level Thermal Sweating Head for Heat Loss

Figure 12: Fit of Different Hoods on Human Subjects at Field Trial

<u>Main takeaways from data</u>:

- A new standard operating procedure was developed to evaluate the total heat loss of firefighter hoods on the sweating thermal manikin headform.
- A simulated coat collar and modified SCBA facepiece were utilized to optimize the testing.
- Testing of multiple types of particulate-blocking and traditional hoods showed that the material-level THL values do not always agree with the performance of the hood when tested on the headform.
- The fit (tightness/looseness) of the hood on the headform appeared to contribute significantly to the ability of heat to escape through the hood.
- The more the material stretched on the headform, the more heat was able to leave the system and vice versa. However, a tighter-fitting hood would most likely result in less thermal protection as there would be direct contact with the skin and very little air gap to serve as an insulator.

Figure 13: Example Impages of Headform Fluorescent Aerosol Testing for Particulate-Blocking[10,11]



Bare Headform – No Hood
Protection Factor = 1

Traditional 2-Layer Knit Hood
Protection Factor = 13.3

2-Layer Particulate-Blocking Hood
Protection Factor = 125.8

Main takeaways from the data:

- While being the only readily accessible full system test for particulate infiltration, this test still has its areas for improvement – mainly the difficulty in preventing and discerning cross-contamination during doffing and before taking the photos.
- Quantitative results showed that of the traditional and particulate-blocking hoods evaluated (at 5 mph wind speed) the lowest performing traditional hood provided ~13x the protection and the best performing particulate-blocking hood provided ~125x protection compared to a bare headform.
- Only images were able to be collected from the second trial (run at 10 mph wind speed), but they showed potential increased particle infiltration at the higher wind speed.
- Durability does not appear to be a significant issue for the particulate-blocking hoods evaluated as they were provided from a local fire department after multiple months of active use and did not show significantly different particulate deposition compared to a new hood.

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[10] The first set of hoods (18) were tested at 5 mph in the wind tunnel and the second trial (9 hoods) was conducted at 10 mph (NFPA standard), but due to testing constraints quantitative sampling was not possible for the second trial.
[11] Half of the first set of hoods consisted of particulate-blocking hoods donated from the Cary Fire Department (NC) after being in service for multiple months.

Figure 14: Particulate Deposition on Outside and Inside of Traditional Hood

Outside of Hood

Inside of Hood

Main takeaways from images:

- Heavy deposition on the outer side (left) of the hood as well as significant deposition on the inner side (right) of the hood show that the area around the face opening on the hood if worn over the frame of the respirator facepiece, is highly exposed to particulates and can potentially be one of the most contaminated areas on the hood.
- This finding is of high concern due to the common practice that firefighters have of pulling the face opening down around the neck to doff the SCBA facepiece after exiting a fire. By placing the highly contaminated face opening around the neck, it is likely that contaminant-rich soot will transfer from the hood material to the skin of the neck, which is one of the most vulnerable body regions for absorption of chemicals.
- This transfer of contaminants would be possible regardless of whether the firefighter was wearing a traditional hood or a particulate-blocking hood, as both would be equally likely to be contaminated on the outer layer.
- Therefore, to limit the possibility of contaminant transfer to the skin, it may be necessary to alter the way in which hoods are doffed and to discourage the practice of pulling the hood down around the neck.

Figure 15: Smoke Outward Leakage Head Form Demonstration

Note: By scanning the QR code above, you will be able to view a video of smoke outward leakage test on a traditional hood

Figure 16: Quantified Smoke Inspection Method (QSIM) – Adopted into NFPA 1851:2020

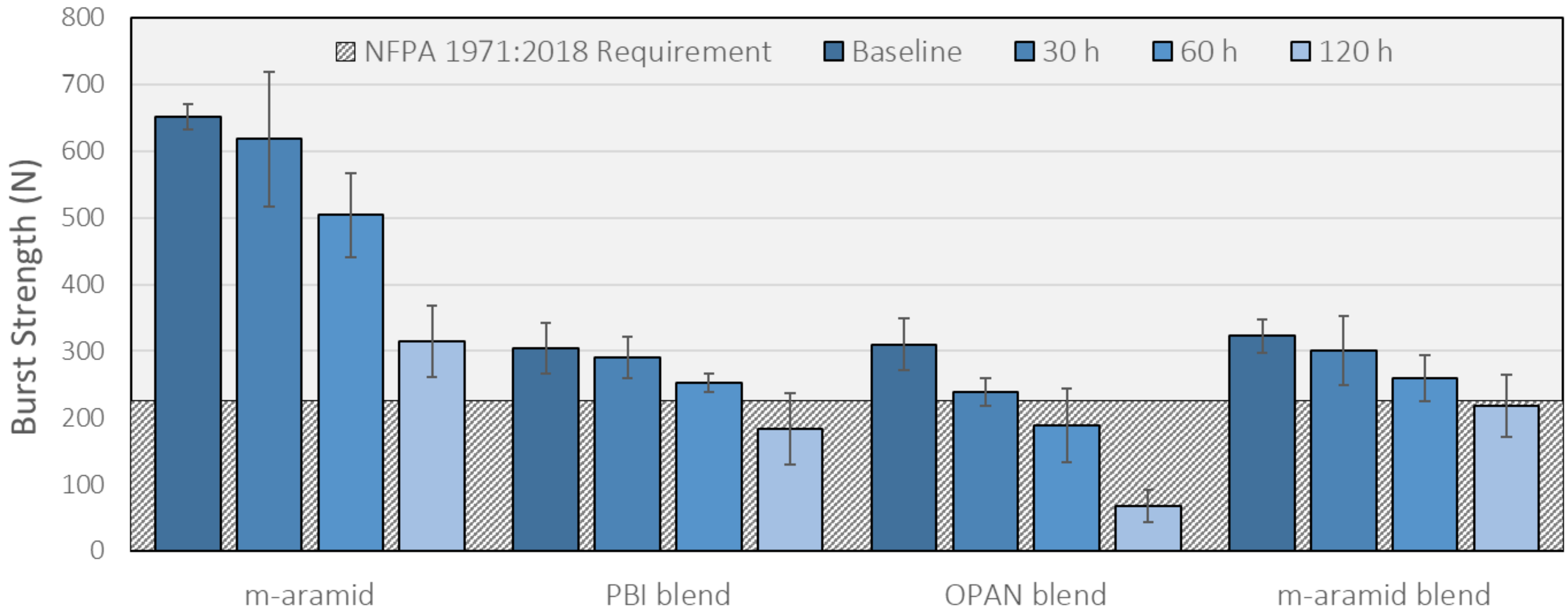
Note: By scanning the QR code above, you will be able to view a video of the QSIM test

Main takeaways from new method:

- The QSIM was designed so that it could be built/purchased for individual fire departments to use in their stations.
- This method provides a non-destructive assessment of a hood's ability to block smoke particles.
- Described in the 2019 Fire Engineering PPE Supplement – January 2019[12]
- This method was adopted into the NFPA 1851:2020 standard as a means to conduct advanced inspections of particulate-blocking hoods.

[12] https://digital.pennwell.com/pennwellevents/fe_january_2019_ppe?sub_id=8FoeKisB2QWq&pg=22#pg22

Figure 17: Effect of Prolonged Exposure to Simulated Sunlight on the Mechanical Strength of Hood Materials



<u>Main takeaways from graph</u>:

- Regardless of the type of outer knit material, all hoods should be kept out of direct sunlight or other sources of UV light as much as possible.
- With more exposure to direct sunlight, the likelihood of damage occuring to the hood increases.

Partners - Institutions, Businesses, or Consultant Partners

Official Subcontracted Partners

Name of Entity	Project Role
Illinois Fire Service Institute (IFSI) • Dr. Gavin Horn • Mr. Richard Kesler	• Role on the project was to conduct field assessments to determine the effect of different hoods on range of motion, hearing, and physiological response of firefighters
International Personnel Protection, Inc. • Mr. Jeff Stull	• Role on the project was to provide technical expertise and guidance for the development of testing methods and for the implementation of research findings into the NFPA and ASTM standards

Unofficial Project Partners – Volunteered or Donated Goods or Services

Name of Entity	Project Role
FireDex, LLC	• Constructed and donated hoods for headform and field testing • Provided field-worn hoods for inspections and fluorescent aerosol testing
Stedfast, Inc.	• Manufactured and donated range of particulate-blocking layers • Provided expertise on materials and testing
Majestic Fire Apparel, Inc.	• Donated multiple rolls of outer knit materials for all aspects of the project
DuPont	• Donated Nomex® NanoFlex materials • Donated particulate filtration efficiency testing on multiple hood composite samples
W.L. Gore & Associates, Inc.	• Donated particulate-blocking materials • Collaborated on development of PyroHead™ evaluation method as well as subflash/radiant testing
LION First Responder PPE, Inc.	• Donated helmets and earflaps for PyroHead™ evaluations
Functional Ideas, Inc.	• Aided in the development of Quantified Smoke Inspection Method
Cotton Incorporated	• Loaned testing apparatus to conduct material burst strength assessments

Unofficial Project Partners – Provided Testing and/or Services

Name of Entity	Project Role
Underwriters Laboratory (UL)	• Performed extended exposures to simulated sunlight for durability assessments
IBR Laboratories	• Performed particulate filtration efficiency testing according to NFPA 1971
RTI International	• Performed headform-level fluorescent aerosol testing

Partners - Fire Service Organizations or Individual Partners

Name of Organization	Project Role
Sandhills Community College – Larry R. Caddell Public Safety Training Center (Carthage, NC)	• Provided access to the training facility and personnel for conducting field trials on hoods • Provided educational opportunities for undergraduate and graduate students to learn about the live fire environment and to experience the facility
Cary Fire Department (NC)	• Provided expertise and insights on firefighter needs and concerns • Collaborated on planning of the field trials and arson training live burn in conjunction with the training center • Provided field worn hoods for chemical testing as well as for durability assessments • Provided additional helmets and SCBA masks for fluorescent aerosol testing
Raleigh Fire Department (NC)	• Provided expertise and insights on firefighter needs and concerns • Provided access to training facility for educational opportunities for graduate students
North Carolina Office of State Fire Marshal (OSFM)	• Provided access with Cary Fire Department to an arson training burn to realistically contaminate hood samples for chemical testing
National Fire Protection Association (NFPA)	• Provided a means to disseminate information about the project to the technical committee responsible for hoods