Advanced Multi-threat Base Ensemble for Responders (AMBER™): Final Report

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March 5, 2018

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Executive Summary

This report documents the Advanced Multi-threat Base Ensemble for Responders (AMBER) research conducted by the Textile Protection and Comfort Center (T-PACC) within the College of Textiles at North Carolina State University (NC State) between September 2014 and December 2017. The Department of Homeland Security (DHS) Science and Technology (S&T) Directorate, First Responders Group (FRG) sponsored T-PACC to develop an advanced multi-threat garment for first responders.

The DHS goals of this program were to develop a new protective ensemble, for daily use by law enforcement (LE), firefighter (FF) and emergency medical service (EMS) personnel, which would provide increased protection from multiple threats when compared to their existing cotton or polyester uniforms. The DHS "Project Responder 3" and "Project Responder 4" Reports identified a priority need for clothing and equipment to protect against "all hazards in an unpredictable response environment" [(1)] [(2)]. The emergency environment and mission for the various types of first responders often overlap, requiring a multi-threat protective base ensemble applicable across multiple operations and compatible with their primary protective gear (e.g. Structural Turnout Gear, body armor, etc.). Currently, no multi-hazard protective ensemble exist for use across multiple responder duties.

Key features of the AMBER ensemble are listed below and illustrated in Figure 1.

- Overall, a functional design integrated with advanced technical textiles for enhanced protection and wearer comfort.
- Comfort, durability, and protection properties optimized for maximum system performance for daily wear.
- System-level limited protection against heat and flame, splash resistance, water resistance, and localized cut and impact protection at the knees.
- Modular design for integration with primary protective clothing against specific hazards, as well as addressing the needs for a wide range of sizes.

Figure 1: AMBER Final Design Features

Fabric and ensemble level testing occurred in T-PACC's research and testing facilities, which enabled systematic testing and evaluation of the developed prototype. Performance assessments included Heat Storage, Heat and Thermal Shrinkage, Thermal Stability and Vertical Flame tests for fire and heat protection, repellency and splash protective tests as well as fabric and system-level evaluation of thermal comfort. Finally, the research team conducted human subject ergonomic and subjective comfort evaluations.

The AMBER system integrates state-of-the-art protective technologies including flame resistance, blood-borne pathogen splash protection, water repellency, optimal daily-wear comfort, integrated kneepads, localized cut and impact protection and deployable reflectivity among other critical features. The AMBER Ensemble is certified to the requirements of the National Fire Protection Association's (NFPA) 1975 Standard on Emergency Services Work Clothing Elements (2014 edition). One hundred fifty (150) certified AMBER prototypes were delivered to DHS for extended operational wear testing.

Approach

T-PACC used a modified system engineering approach during development of the AMBER ensemble. This approach consisted of rigorous needs analysis and requirements development to ensure traceability of user needs throughout. T-PACC also used data-driven multi-criteria decision-making methods during material and design selection to optimize ensemble performance. T-PACC subcontracted with Protect the Force Inc. (PTF), a company that has a distinguished record of accomplishment in developing and fielding new products for a wide range of military and first responder applications, for this development effort. PTF assisted with the design process during prototype development. PTF was responsible for the certification of the AMBER garments to the National Fire Protection Association (NFPA) 1975 Standard on Emergency Services Work Clothing Elements as well as the production of 150 certified prototype garment ensembles. PTF will also lead commercialization activities that follow completion of NC State's research. The DHS Science and Technology Directorate's vision for the AMBER garment, along with input from the

DHS - S&T First Responders Resource Group (FRRG) provided direct user support throughout the project, aiding in creating a user-centric solution with high user acceptability across different First Responder groups.

Target End User Developmental Framework

The DHS Statement of Objectives (SOO) for the base ensemble project stated that the garment should be designed to enhance protection for all first responders while wearing their normal duty uniforms [(3)]. The SOO also included a need for protection from a variety of potential hazards. Due to the inherent difficulty in trying to protect all first responders from all the hazards, and in order to effectively scope requirements for a feasible and successful protective ensemble, T-PACC, with collaboration from DHS S&T, developed an initial prioritized user framework. Though each first responder user group has a similar baseline requirement for daily protection needs in a duty uniform, each group (firefighter, law enforcement, emergency medical services) does have unique needs, making it difficult to develop a single solution that meets all protection needs for each first responder. The framework identified priorities, allowing for a more focused development process, while still capturing the needs of all groups. The developmental framework elements are listed below and illustrated in Figure 2.

- 1°-Firefighter and Emergency Medical Services
- 2°-FF, EMS and Law Enforcement
- 3°-EMS/LE or FF/LE users

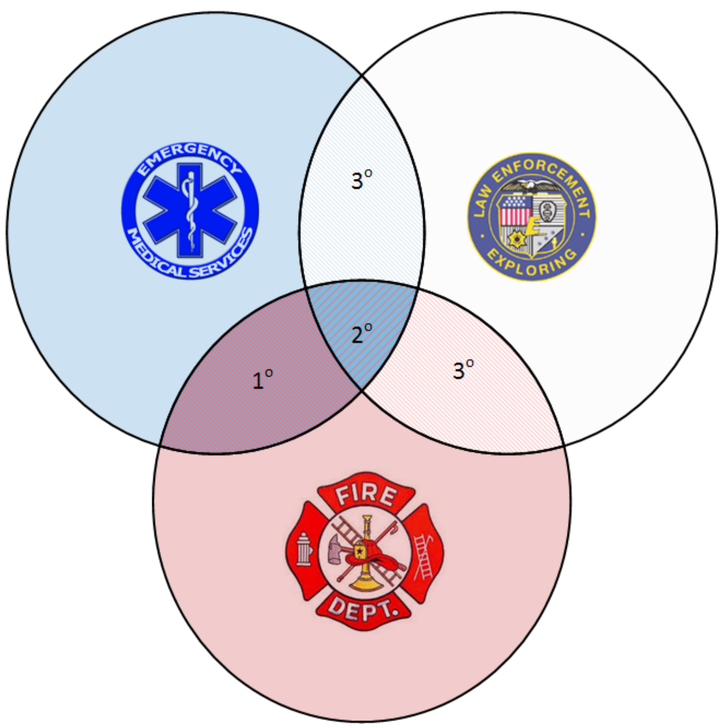


Figure 2: AMBER Developmental Framework by Targeted User Groups

Though this framework was used to focus the requirements development process it did not preclude the team from considering needs from all user groups. The participants from DHS's First Responder Resource Group (FRRG) were from all user group areas and all user groups were represented in various user feedback sessions throughout the project development.

Solution Objectives

Per the Statement of Objectives within the BAA 13-012/Call 0001/SOO G – Base Ensemble for First Responders Statement of Objectives [(3)], the new base ensemble will:

- Provide enhanced personal protection for first responders in performing the majority of their normal daily activities and provide an improved level of protection, when compared to their existing duty uniforms, in the event they encounter unexpected hazards.
- Be compatible with specialized protective garments and existing first responder tools and equipment to meet mission-specific requirements.
- Reduce fatigue, improve human performance factors, increase initial responder protection, and support specialized missions.
- Be designed to protect against typical[1] hazards, atypical[2] hazards, and unexpected[3] hazards.
- Have the following features:
    - Protection from elements
    - The ability to integrate padding in various locations in the garment (such as knees, elbows, and shoulders)
        - Provides localized stab/penetration/tearing protection

See APPENDIX A: Background for additional background on source documentation and target users.

[1] Typical hazards (those that a responder trains for and where existing Personal Protective Equipment (PPE) provides some level of protection).
[2] Atypical hazards (such as those for which existing training and/or PPE may be insufficient).
[3] Unexpected hazards (to include circumstances for which a first responder may have neither the training nor PPE to respond effectively but from which they need protection to escape).

Development Process

We used a system engineering (SE) approach during this effort. An SE approach is a multidisciplinary approach to the development and management of `complex systems'. It optimizes total system performance through an integrated and disciplined focus on balancing cost, schedule, performance, and risk. [4] In this case, the overall end garment defines the system and the objectives identified in the BAA document represent the operational needs of the end user. The SE approach is particularly well suited to take user input and translate them through needs analysis into overarching performance needs, then into design requirements. T-PACC conducted the needs analysis early in the project, developed the Key System Needs as the basis for creating Key Performance Parameters (KPP), high-level performance parameters traceable to the operational needs. This approach incorporated direct user feedback in each Phase of the project. We obtained valuable input on user requirements and response to AMBER prototype design iterations from local Raleigh/Durham Firefighters and EMS personnel, along with DHS's First Responder Resource Group (FRRG).

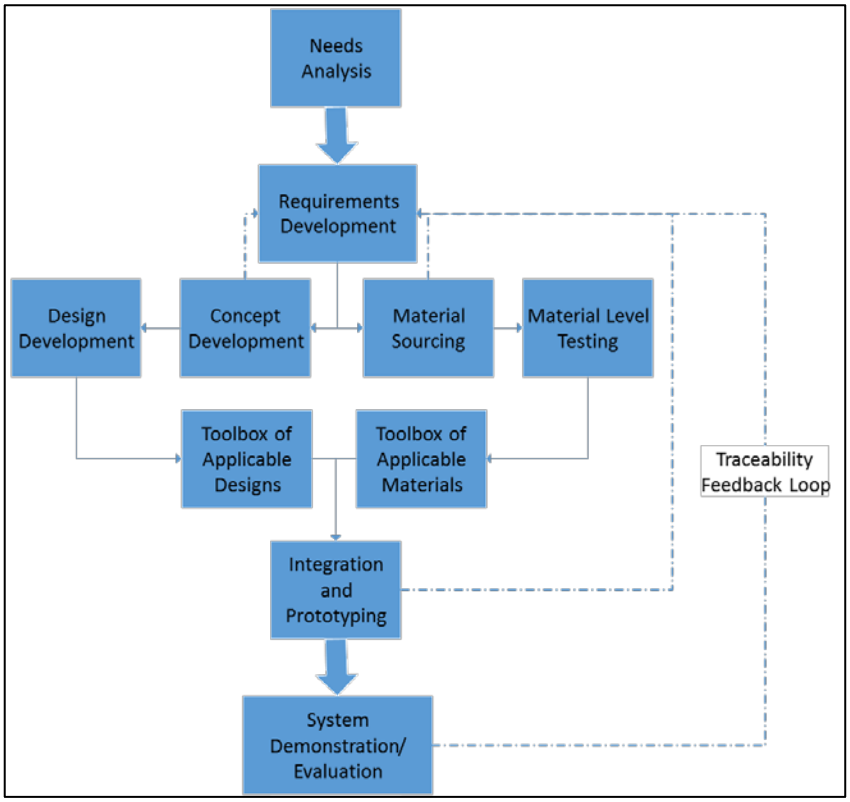


Figure 3: Process Flowchart

Design requirements were developed based on the higher-level KPPs, ensuring traceability back to the key needs. Based on these requirements, the T-PACC team concurrently worked on identifying material technologies and system-level concepts that could meet the performance requirements. With user feedback throughout each Phase of the project, the materials and design concepts were integrated into fully defined concepts and initial designs. Iterative designs, material and system testing, and a subjective user trial were used to help finalize designs for prototype production. A process map is shown in Figure 3.

Market Research

To understand the user market, the team assessed existing base ensembles available to first responders through popular online websites that exclusively sell first responder uniforms, apparel, and gear. This market research revealed popular choices in fabrication, fiber content, and garment style, along with average retail prices. From this, it was established that a button-down shirt with collar and pants were most popular amongst station wear uniforms and widely available for purchase. This style and aesthetic established the baseline for AMBER in terms of testing, design, and subjective questioning.

Baseline Garment Systems

When developing a new garment system designed to address deficiencies in current systems available in the market, it is important to identify a baseline system or systems as a performance benchmark. In order to compare AMBER to the best in the market for the desired performance attributes, the team selected three baseline ensembles that represent a range of currently available systems (Table 1). This project aimed to produce a system that limits the impact on comfort when adding protection. Thus, both high protection and high comfort were key variables to developing AMBER. Additionally, to ensure the overall system cost at the end of the effort is feasible from a commercialization perspective, T-PACC felt it necessary to include a lower cost protective system. Therefore, it was important to identify systems currently marketed as comfortable, protective, and low cost but protective. T-PACC chose a high protective system, a high comfort system, and a low-cost system, representing three key priorities within the overall development of a garment system.

Table 1: Market baseline garment systems chosen for use during the AMBER program.

Baseline 1: Blauer Station Uniform **Assumption: (Lower Cost)**	**Baseline 2: Lion Station Uniform** **(Higher Protection, Lower Comfort)**	**Baseline 3: 5.11 Taclite Pro ensemble** **(Higher Comfort, Lower Protection)**
•100% Cotton •NFPA 1975 Certified •4-pocket trouser •Traditional style •Geared towards firefighter applications •Mid-Low range cost	•Nomex®IIIA •93% Nomex®, 5% Kevlar®, 2% antistat • NFPA 1975 Certified •Traditional style •Workwear weight •No functional design elements •Highest Cost	•65% Polyester, 35% Cotton •No certification •multiple functional design elements •geared towards EMS application •Lightweight •Mid-Low range cost

Needs Analysis

This analytical process took DHS identified needs and translated those into overarching performance parameters. The Key Performance Parameters prioritized user acceptance for daily wear and protection based on those concerns identified in Project Responder 3 and Project Responder 4.

The user needs analysis focused on readily available information contained in documentation generated as part of Project Responder 3 and Project Responder 4 reports, along with published documentation, adopted standards and specific program level input from DHS S&T and the FRRG as related to the overall goals of the program. Documentation that formed the basis for this analysis are:

- Project Responder 3 [1]
- Project Responder 4 [2]
- BAA 13-012/Call 0001/SOO G – Base Ensemble for First Responders Statement of Objectives [3]

- NFPA 1975-2014 (5)

With support from the DHS Program Manager, user feedback was included throughout the program. The Key System Needs summarize the operational, functional, stakeholder, and performance attributes for the desired final AMBER system. The key system needs also helped to prioritize needs, aiding in tradeoff decisions during development.

During the needs analysis process, it was determined that fundamental to the overall performance of the solution was the need for the AMBER garment to meet an established certification, in this case, NFPA 1975 was preferred. It was also determined that any final garment design, in order to be accepted by users as a daily wear uniform, would need to be comfortable and durable on a daily basis. Direct user feedback also indicated that there was a desire for the garment system to provide usability/functionality, fit the desired aesthetics required of a first responder garment, and increase multi-threat protection. These key needs were used as the basis for developing the Key Performance Parameters (KPPs).

Key System Needs:

- User Comfort
- Durability for Daily Wear
- Usability/Functionality
- Aesthetics
- NFPA 1975 Certification
- Multi-service applicability
- User acceptability
- Reasonable cost
- Enhanced Protection
- Optional Tradeoff Protection

Key Performance Parameters

KPPs were developed using the Key System Needs and form the basis for the desired AMBER system performance tradeoffs. Table 2 shows the KPPs developed for AMBER. It is important to note that all of the KPPs listed are underpinned by the constraint requirement for NFPA 1975 certification. While each KPP has some potential for tradeoffs, NFPA 1975 certification was deemed as an absolute requirement by DHS, so it was not included as a KPP here. Additionally, the Key System Needs identified above but not included in the KPPs below (reasonable cost, user acceptability, enhanced protection, optional tradeoff protection and multi-service applicability) were still used as developmental considerations and opportunities.

Table 2: Key Performance Parameters

#	Product	Key Performance Parameters (KPP)
KPP #1	System Level Ensemble	***User Comfort****-Generally meaning the characteristics that indicate to a user that the ensemble system is comfortable for daily, extended wear (total heat loss, moisture management properties, moisture vapor transmission rate, air permeability, fit, functional design elements, etc.)*
KPP #2	Material and System Level Ensemble	***Durability for Daily Wear-****Described as the properties of the materials used or system level ensemble that impacts the use life of the system (abrasion, tear strength, UV degradation, seam strength, etc.)*
KPP #3	System Level Ensemble	***Usability****-Defined as the ability for the system level ensemble to have value-added functionality for the user within specified target end user applications.*
KPP #4	System Level Ensemble	***Aesthetics****-Defined as the appearance of the system.*

APPENDIX B: Requirements Development provides additional information on the overall requirements development process. Table 26 in APPENDIX B: Requirements Development provides the linkages between key system needs and performance parameters with associated test methods used for measurement.

Summary of Results

Test results for key performance attributes for fabric and system level assessments of candidate materials and controls are presented below in Table 3. See APPENDIX C: Concept Development and APPENDIX D: Material Selection for additional details on the concept development, materials selection process, and trade space decision methods used for down selection of optimum fabrics and prototypes.

Unit Abbreviations

Abbreviations used in the results summary along with their measured properties are described in Table 3.

Table 3: Unit Abbreviations

Unit Abbreviation	***Unit***	***Property***
oz/yd^2	ounces per square yard	fabric basis weight
lbf	pounds-force	force
N	newton	force
W/m^2 or Q	Watts per square meter	heat flux
$	dollars	currency
In	inches	length
sec	seconds	time
min	minutes	time
gf	gram-force	force
kN	kilonewton	force
mm	millimeter	length
cm	centimeter	length
ft	foot	length
$ft^{3/}min/ft^2$	cubic foot per min per square foot	air permeability
$gf*cm^2/cm$	gram-force * square centimeter per centimeter	fabric stiffness
gf/cm*degree	gram-force per centimeter *degree	fabric drape
$g/m^2/24hrs$	grams per square meter per 24 hours	Moisture Vapor Transmission Rate
m/s	meters per second	speed
RH	Relative Humidity	Relative Humidity
°C	Celcius	Temperature
Kpa	KiloPascal	Pressure

Selected Materials

Three main areas of material sourcing were conducted based on concepts developed: woven pant/shirt (Type 1), stretch panel performance knits (Type 2), and a membrane/laminate technology (Type 3). An extensive marketplace search was conducted for each type of material, with over 50 materials reviewed. The commercially available products chosen for use in AMBER prototype garment construction are shown in Table 4. Additional information on the downselection process and decision-making can be found in APPENDIX D: Material Selection Methods, APPENDIX E: Material and System Test Method Descriptions, and APPENDIX F: Down-selection Results by Phase.

Table 4: Commercially available materials used in AMBER

Style ID	**Manufacturer**	**Fiber Content**	**Construction**
580A	Tencate	Modacrylic, Cellulose, Aramid	Woven

Style ID	Manufacturer	Fiber Content	Construction
700A	Tencate	Modacrylic, Cellulose, Aramid	Woven
Blaze	Massif	93% Cotton, 7% Spandex	Knit
TX4100	Agrotec	polyurethane	Film

For material down selection, a quantitative decision-making support tool was developed. This analytical procedure employs the weighted properties method combined with a digital logic method to link performance measures and need priorities to test values. Generally, the overall objective of decision-making was to ensure that the materials chosen represented a durable, more comfortable, and more protective alternative to the current baseline systems. A rigorous data-based trade space analysis helped inform the material selection processes. Further details on the selection methods are found in APPENDIX D: Material Selection Methods and APPENDIX F: Down-selection Results by Phase. Based on this down-selection process, along with the considerations of NFPA 1975 certification, practical/feasibility constraints, and cost, the final material combinations along with their added treatments, location on the garment, and performance attributes are shown below in Table 5.

Table 5: Final Materials Selected for use in NFPA 1975 certified AMBER prototypes

Material Type	Material Names	Treatments Applied	Material Location	Key Performance Attributes
Type 1	Tencate 580A	Antimicrobial, DOR*,	Shirt	Optimized FR*, Cost, & Comfort
Type 1	Tencate 700A	Antimicrobial, DOR*,	Pant	Optimized FR*, durably treatable for AM* & DOR*, cost & comfort
Type 2	Massif Blaze	None	Shirt back vent, leg vent, back go knee, crotch gusset, back yoke	Stretch and recovery, moisture wicking, FR*, & pass thermal stability & shrinkage
Type 3	Tencate 700A/TX4100/Massif Blaze	DOR*	Pant knee	Best combination of liquid protection & flexibility

*FR=Flame Retardant, AM=Antimicrobial, DOR=Durable Omniphobic Repellent

Material Level Performance

Note: Material level performance data presented in this report refers to the final materials selected for the final AMBER design (described in Table 5) and thus certified to NFPA 1975 base requirements unless otherwise noted. This includes any treatments applied to the commercial fabrics during development.

Comfort

Particularly important to the AMBER concept is system comfort. For AMBER, comfort was defined by the combination of several performance attributes, such as total heat loss (ASTM F1868), air permeability (ASTM D737), fabric stiffness (Kawabata-bending rigidity), fabric drape (Kawabata-shear), and vertical wicking (NC State Method). Table 6 and Table 7 shows the comfort performance of the AMBER Type 1 woven materials alongside baseline woven materials. Test method descriptions are in APPENDIX E: Material and System Test Method Descriptions.

Table 6: Woven baseline comfort comparison to AMBER Type 1 materials (Part 1)

Fabrics	Basis Weight	Total Heat Loss	Air Permeability	Vertical Wicking
	oz/yd²	W/m²	ft³/min/m²	inches (@ 5 min)
Baseline 1 - Cotton	6.3	568.8	23.2	7.42
Baseline 2 - Nomex®IIIA	4.7	636.8	221	6.83
Baseline 3 - Poly/Cotton	4.8	541.9	39.4	0.5
Tencate 580A	6.2	754.5	82.8	8.15
Tencate 700A	7.9	741.8	46.7	7.25

Table 7: Woven baseline comfort comparison to AMBER Type 1 materials (Part 2)

Fabrics	Basis Weight	Stiffness	Drape
	oz/yd²	gf*cm²/cm	gf/cm*degree
Baseline 1 - Cotton	6.3	0.090	0.729
Baseline 2 - Nomex®IIIA	4.7	0.108	0.471
Baseline 3 - Poly/Cotton	4.8	0.075	1.119
Tencate 580A	6.2	0.091	0.583
Tencate 700A	7.9	0.140	0.886

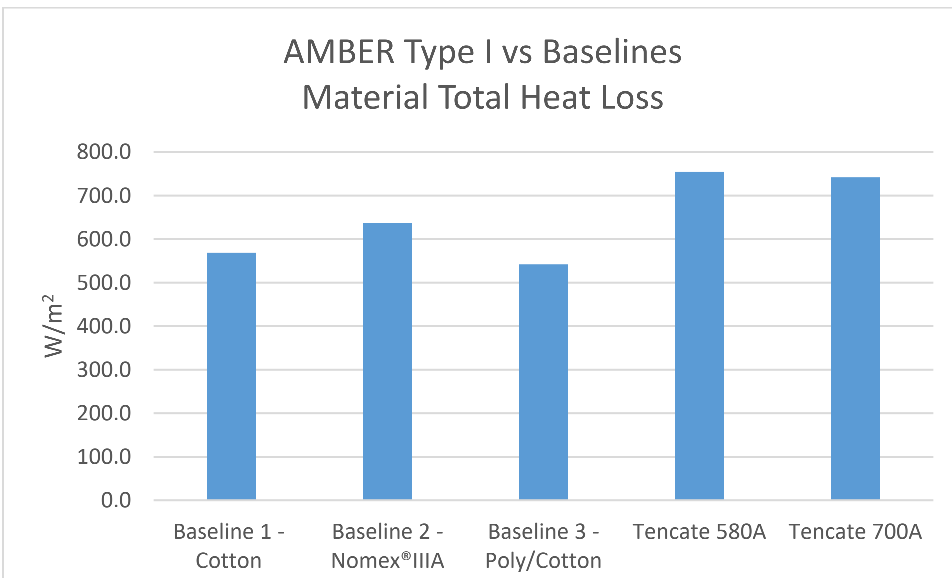


Figure 4: AMBER Type 1 Material Total Heat Loss Baseline Comparison

Total Heat Loss (THL) is a key performance measure in thermal comfort of clothing materials and is a measured index that indicates breathability of a clothing fabric. A higher THL value is associated with better thermal wear comfort. The higher the heat loss, the more a fabric dissipates the heat generated by the wearer during use. When compared to baseline materials, both Type 1 woven materials chosen for AMBER had the highest THL values, despite being two of the heavier fabrics (Table 6). With the exception of Baseline 2 – Nomex®IIIA, the AMBER materials had higher air permeability. Tencate 580A is also more pliable (drapeable) than baselines with similar and lower weight (Table 7). In most other comfort categories, the AMBER Type 1 materials were comparable to the performance of the baselines.

The second material critical to AMBER system design is a performance knit used in strategic locations for added comfort and functionality. No knit materials exist in any of the baseline garment systems. Thus, direct comparisons of comfort data to the baseline woven materials do not provide a performance comparison. Therefore, the comfort data for the Type 2 performance knit material is presented in Table 8 and Table 9.

Table 8: AMBER Type 2 material comfort performance (Part 1)

Fabrics	Basis Weight	Total Heat Loss	Air Permeability	Vertical Wicking
	oz/yd^2	W/m^2	ft^3/min/m^2	inches (@ 5 min)
Massif-Blaze	6.9	580.91	88.3	4.65

Table 9: AMBER Type 2 material comfort performance (Part 2)

Fabrics	Basis Weight	Stiffness	Drape
	oz/yd^2	gf*cm^2/cm	gf/cm*degree
Massif-Blaze	6.9	0.03095	1.3185

The primary benefit for use of a knit material in AMBER is to enhance user comfort during movement by reducing the resistance of the garment on the body. Knit mechanical properties of high drape, low stiffness along with stretch, when placed in strategic locations (as done in the AMBER garments - see Table 5) enhance comfort and functionality during use.

Durability of Daily Wear

Durability during daily wear is another key performance parameter for the AMBER system. Test results for abrasion resistance (ASTM D4966), tear strength (ASTM D1424), and break strength (ASTM D5034) are provided in Table 9. Test method descriptions are in APPENDIX E: Material and System Test Method Descriptions.

Table 10: Woven material baseline durability performance comparison to AMBER Type 1 materials

Fabrics	Basis Weight	Abrasion	Tear Strength	Break Strength
	oz/yd^2	cycles	lbf (N)	lbf (N)
Baseline 1 - Cotton	6.3	36001	6.30	78.20
Baseline 2 - Nomex®IIIA	4.7	34333	11.54	153.75
Baseline 3 - Poly/Cotton	4.8	36001	4.81	118.50
Tencate 580A	6.2	14333	10.50	92.50
Tencate 700A	7.9	25333	9.00	110.00

In general, baseline materials provide higher durability to abrasion as compared to the AMBER Type 1 materials. However, tear strength and break strength were comparable to the baseline materials, with the exception being Baseline 2 – Nomex®IIIA, known to be a high strength fiber. Based on the overall tradeoff analysis for Type 1 materials, as seen in APPENDIX F: Down-selection Results by Phase, protection, and comfort were prioritized over durability.

Results for burst strength (ASTM D3787) and pilling resistance (ASTM D3512), both characteristics of wear durability, are shown in Table 11 for the Type 2 AMBER knit material. The selection process and additional information on how the selected AMBER Type 2 material compares to other knit materials are found in APPENDIX F: Down-selection Results by Phase.

Table 11: AMBER Type 2 material durability performance

Fabrics	**Basis Weight**	**Burst Strength**	**Pilling Resistance**
	oz/yd^2	**lbf**	**Visual Rating**
Massif-Blaze	6.9	72.2	5

Protection

Inherent to the success of the AMBER system as a daily wear system is its ability to provide added protection against multiple types of threats. For AMBER, this is defined as limited system protection or localized protection from some daily hazards. On the fabric level for AMBER, this is defined as flame resistance (ASTM D6413), liquid splash resistance (AATCC 118 and ISO 6530) and localized enhanced puncture resistance (ASTM F1342). The localized protection provided at the component level (kneepads) is summarized in the following section. Test method descriptions are in APPENDIX E: Material and System Test Method Descriptions.

Figure 5 and Figure 6 demonstrate the flame resistance of the AMBER materials compared to the baseline materials.

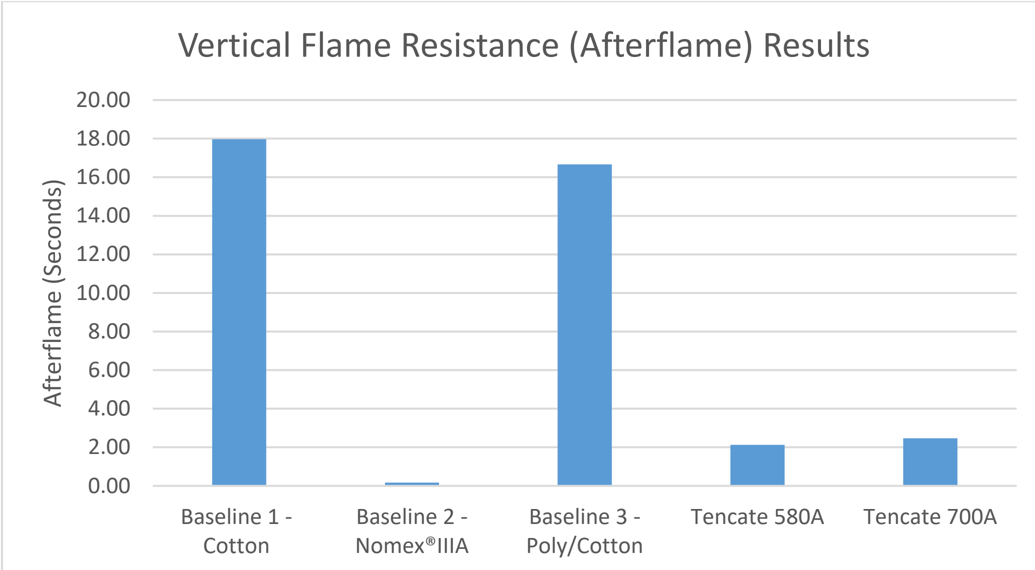


Figure 5: AMBER Type 1 woven materials flame resistance (Afterflame) performance baseline comparison

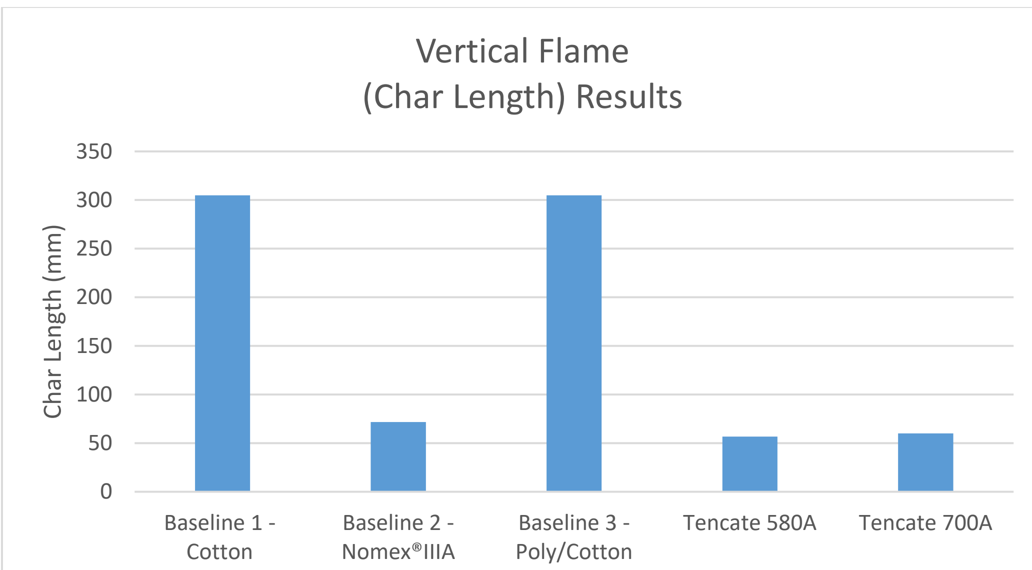


Figure 6: AMBER Type 1 materials flame resistance (Char Length) performance baseline comparison

The AMBER TYPE 1 woven materials have as good or better flame resistance and comparable puncture resistance when compared to the baseline materials. Additionally, the AMBER materials along with the baseline Nomex®IIIA and baseline cotton materials passed the NFPA 1975 thermal stability and the heat and thermal shrinkage resistance testing required for certification.

Table 12: Woven material baseline protective performance comparison to AMBER Type 1 materials

Fabrics	**Basis Weight**	**After Flame**	**Char Length**	**Puncture (ASTM)**
	oz/yd^2	**seconds**	**mm**	**N**
Baseline 1 - Cotton	6.3	17.97	305	7.56
Baseline 2 - Nomex®IIIA	4.7	0.17	72	10.68
Baseline 3 - Poly/Cotton	4.8	16.67	305	20.02
Tencate 580A	6.2	2.13	57	9.34
Tencate 700A	7.9	2.47	60	14.23

Table 13: NFPA 1975 Heat and Thermal Shrinkage Resistance and Thermal Stability Pass/Fail results

Fabrics	**Heat and Thermal Shrinkage**	**Thermal Stability**
	NFPA 1975-2014 Sec 8.2	**NFPA 1975-2014 Sec 8.3**
Baseline 1 - Cotton	Pass	Pass
Baseline 2 - Nomex®IIIA	Pass	Pass
Baseline 3 - Poly/Cotton	Fail	Fail
Tencate 580A	Pass	Pass
Tencate 700A	Pass	Pass

Test results of Vertical Flame resistance for Afterflame and Charlength, are shown in Table 14 for the Type 2 AMBER knit material. The AMBER Type 2 knit material also passed all required NFPA 1975 certification testing. The selection process and added information on how the selected AMBER Type 2 knit compares to other knit materials are found in APPENDIX F: Down-selection Results by Phase.

Table 14: AMBER Type 2 material flame resistance performance

Fabrics	**Basis Weight**	**After Flame**	**Char Length**
	oz/yd^2	**seconds**	**mm**
Massif-Blaze	6.9	0.1	88.33

Liquid resistance is also incorporated into the AMBER Type 1 woven materials (Tencate 580A and 700A) via textile treatment with a Durable Omniphobic Repellent (DOR) finish. This textile finish imparts both water and oil repellency behavior and provides some additional repellency against liquids commonly contacted as a first responder. The development of the textile finishes is described in APPENDIX G: Material Finish Technology. The liquid repellency of the final AMBER Type 1 woven fabrics were measured with the ISO 6530 method. Liquids used were deionized water, the 5 chemicals identified in NFPA 1971, section 8.27.4.2 (Aqueous film-forming foam, Battery acid (sulfuric acid), Fire-resistant hydraulic fluid, Gasoline, and 65% Chlorine), and a blood simulant. The liquid resistance data for the baseline materials are shown side by side to the AMBER Type 1 materials in Figure 7 and Table 15. Test method descriptions are in APPENDIX E: Material and System Test Method Descriptions.

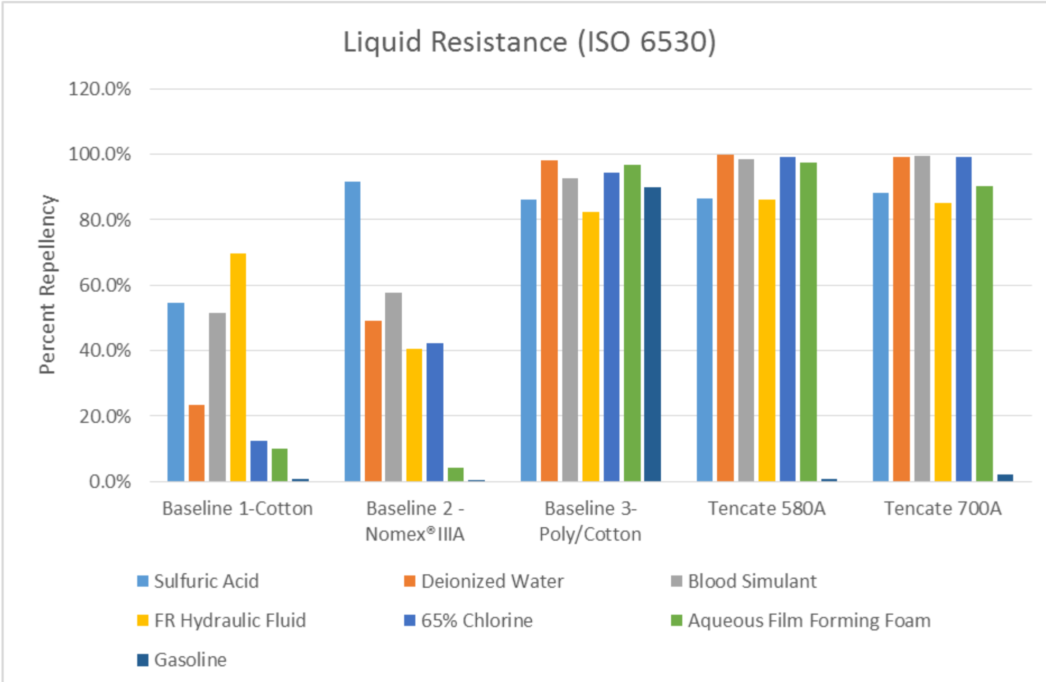


Figure 7: AMBER Type 1 material liquid repellency performance compared to baseline materials

In most cases, the final AMBER Type 1 fabrics when treated with the DOR finish had a higher percentage of repellency as compared to the baseline fabrics. Gasoline was a notable exception, with only the polyester/cotton baseline material performing well for this liquid. It should be noted that the DOR finish (when treated on other fabric types) has demonstrated better performance to gasoline than what was achieved during this effort. The performance of gasoline on the AMBER materials is likely to improve as commercial finishing processes are refined moving forward.

Table 15: Woven baseline liquid repellency performance comparison to the final treated AMBER Type 1 materials (Percent Repellency)

Challenge Liquid	**Baseline 1-Cotton**	**Baseline 2 - Nomex®IIIA**	**Baseline 3-Poly/Cotton**	**AMBER Type 1-Tencate 580A**	**Tencate 700A**
Sulfuric Acid	54.8%	91.5%	86.1%	86.7%	88.2%
Deionized Water	23.5%	49.1%	98.2%	99.7%	99.3%
Blood Simulant	51.6%	57.7%	92.8%	98.6%	99.7%
FR Hydraulic Fluid	69.7%	40.7%	82.3%	86.2%	85.1%
65% Chlorine	12.5%	42.4%	94.2%	99.2%	99.2%
Aqueous Film Forming Foam	10.1%	4.3%	96.7%	97.5%	90.3%
Gasoline	0.8%	0.1%	89.8%	0.7%	2.2%

Enhanced Protection

The AMBER design concept provides enhanced protection in localized areas (such as the knee and shin) that may be more susceptible to certain hazards. This allows enhanced protection with minimal impact on overall garment function or comfort. For example, when a firefighter or an EMT kneels next to a patient when administering CPR or first aid, they may likely kneel in debris, blood or other liquids at a scene. The AMBER kneepads include a multi-layered tri-laminate membrane material for added liquid penetration resistance, and an ergonomically shaped pad, directly molded onto a cut-resistant engineered yarn knit material for added impact and cut protection in the knee and shin areas.

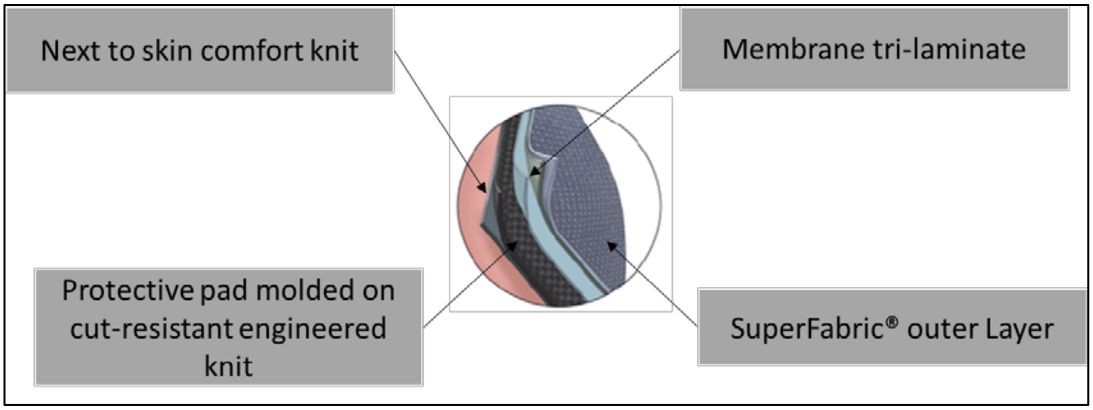


Figure 8: AMBER kneepads depiction

Table 16 and Table 17 demonstrate the added cut (ASTM F1790 with ANSI/ISE 105 levels) and impact (Ball Drop impact test-Ansell Method) protection achieved by integrating the kneepads into the AMBER prototype system. Test method descriptions are in APPENDIX E: Material and System Test Method Descriptions.

Table 16: AMBER material cut protection performance

Fabric Layer(s)	ANSI/ISEA 105 Cut Resistance Performance Level	Cut force (gf)
Knee Pad Composite	4	1655
Super Fabric Only	3	1386
Baseline 1-Cotton	1	406
AMBER Pant (Tencate 700A)	1	485

Table 17: AMBER Knee Pad Composite impact protection performance

Impact Resistance	Thickness (mm)	Impact Force (kN)	% Force Attenuation
AMBER Pant (Tencate 700A)	0.63	18.65	0%
Knee Pad Composite	3.50	7.31	61%
D3O® (Non_FR impact material)	5.44	3.04	84%

The kneepad composite significantly adds to cut resistance protection of the garment in the knee area. At 3.5 mm in thickness, the molded padding composite attenuates ~61% of a direct impact force. Compared to other leading padded materials on the market (such as D30®), the AMBER molded kneepad provides good impact attenuation with lower thickness, and still maintains the flame resistant characteristics of the rest of the AMBER system. Since the kneepad composite does include an elastomeric material as a significant part of the kneepad, the team wanted to ensure that the kneepad component parts would not store heat at low levels of exposure and then cause user contact burns when the material touches the skin. Therefore, stored energy testing (ASTM F2731) was conducted to ensure that the kneepads did not add to potential burn injuries from stored heat. The stored energy test method description is in APPENDIX E: Material and System Test Method Descriptions.

Table 18: AMBER Knee Pad stored energy performance compared to AMBER Type 1 pant material

Description	Time to 2nd Degree burn (sec)
AMBER Type 1 (700A) @ 120 sec	62.4
Kneepad @ 120 sec	129.3
Kneedpad @ 60 Sec	No 2nd Degree Burn

Note: Lower time to 2nd-degree burn indicates lower protection level.

The kneepad stored energy results show that the kneepad doubles the time it would take for a 2nd-degree burn to occur, providing confirmation of its suitability for use in the AMBER garment system.

System Level Performance

Final Design

The final deliverable of the AMBER research included the production of 150 NFPA 1975 certified prototypes. DHS plans to distribute supplied prototypes to FRRG members as part of an extended wear test.

Final garment features include full garment fire resistance (FR), liquid repellency, and antimicrobial treatment. Liquid repellency throughout the system offers biological splash resistance and water repellency for a durable ensemble and added protection for the responder in an unexpected instance of biological hazards. The added antimicrobial finish also aids in providing the responder with longer wearability and comfort and is enhanced in key areas of the shirt (underarms) and pants (gusset and back yoke) with the antimicrobial treated knit material.

Protective design features for the shirt include a deployable reflective strip attached to the back collar. With a simple flip, the wearer or a colleague can deploy this in times where increased visibility is desired. This feature is also found on the pocket bags of the AMBER pant. A feature unique to the AMBER pants is located in the knees with integrated kneepads for impact attenuation. This knee area is further constructed with a specifically developed tri-laminate composite that gives liquid penetration resistance and cut resistance. The back of the knee is comprised of the knit fabric to offer maximum comfort for this area, along with adjustable cords for a secure fit to the knee while in motion and moving from a standing to holding a kneeling position.

Along with enhanced protective design features, the AMBER shirt is designed with articulated shoulders and knit side panels that run the length of the shirt, which aids upper body mobility and next to skin comfort. With a zipper closure and faux button placket, donning the AMBER shirt is quick, while keeping comfort high, but still providing for a professional appearance.

AMBER pants incorporate a wide padded waistband to help alleviate the weight and uncomfortableness found with wearing utility belts while on duty. The inner waistband also possesses a "no-slip" grip silicone strip to keep the wearer's shirt tucked and in place. AMBER pants also have a reinforced, durable seat and stretch gusset and back yoke for lower body mobility and ease of movement. Lastly, zipper vents located diagonally across the upper thighs, are featured for thermal comfort. A summary list of AMBER design features is found in Table 19 with an illustration of the design shown in Figure 9.

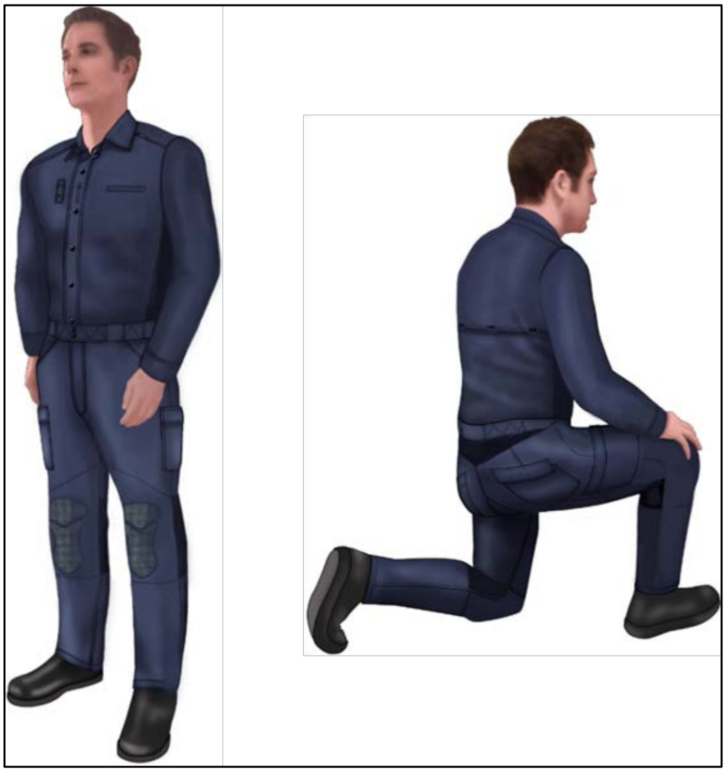


Figure 9: Illustration of Final AMBER design

Table 19: AMBER features list

AMBER Shirt	
Location	**Protective/Design Feature**
Front	Zipper closure with faux button placket
Back and shoulders	Articulated shoulders and back
Back and sides	Knit panels to enable stretch and mobility
Collar	Deployable reflective tab for high visibility
Shoulders	Accessory tabs

AMBER Pant	
Location	**Protective/Design Feature**
Waistband	Wide and quilted for support, no-slip grip interior
Back yoke and gusset	Knit panels for stretch and mobility
Pockets – back	Large and angled for ease of access
Pockets – front	Cargo style with ample storage, deployable reflective trim
Knee – front	Tri-laminate composite that offers impact protection, liquid penetration resistance, and enhanced cut resistance
Knee – back	Knit paneling with adjustable cords for secure fit
Thigh	Zipper ventilation

System Thermal Comfort Testing

The NC State sweating manikin system is a "Newton" type instrument designed to evaluate heat and moisture management properties of clothing systems. This instrument simulates heat and sweat production making it possible to assess the influence of clothing on the thermal comfort process for a given environment. Simultaneous heat and moisture transport through the clothing system and variations in these properties over different parts of the body can be quantified.

The test ensembles were measured for thermal and evaporative resistance (see Figure 10). The thermal resistance of the ensembles were measured according to ASTM F 1291 “Standard Method for Measuring the Thermal Insulation of Clothing Using a Heated Manikin”. The evaporative resistances were measured according to ASTM F 2370 “Standard Test Method for Measuring the Evaporative Resistance of Clothing Using a Sweating Manikin”.

Figure 10: AMBER prototype system as tested on the heated sweating manikin

In order to ensure the overall system level comfort performance was comparable to baseline systems and the AMBER prototypes met the overall project performance goals, the system level heated sweating manikin testing was conducted. Tests for thermal resistance occurred in non-isothermal conditions; tests for evaporative resistance were carried out under isothermal conditions. The testing conditions used are shown in APPENDIX H: Heated Sweating Manikin Test Conditions.

Table 20: Heated Sweating Manikin predicted heat loss ($Q_{predicted}$ (W/m^2)) baseline versus AMBER prototype

Ensemble	$Q_{predicted}$ walking (1 m/s wind, 25ºC, 65% RH) – W/m^2	$Q_{predicted}$ standing (0.4 m/s wind, 25ºC, 65% RH) – W/m^2
Baseline 1-Cotton	308.4	160.8
Baseline 2 –Nomex®IIIA	318.2	168.9
Baseline 3-Poly/Cotton	282.0	141.5
AMBER prototype	271.9	149.2

The predicted total heat loss ($Q_{predicted}$) for the AMBER prototype was slightly lower than for baseline systems when compared in both walking/medium wind and standing/no wind conditions. If conditions were ideal, and in a controlled environment, it may be possible to detect differences in some cases between the baseline and AMBER garments in terms of thermal comfort. However, based on the fabric total heat loss data, user feedback, and the differences in designs and fit between AMBER and the baseline garments, it is unlikely that any thermal comfort differences would be detected by a user in a field environment. The AMBER garments were tested with a closed vent configuration and AMBER includes a kneepad composite, which may provide added heat retention to the system, slightly increasing the AMBER system values. The most likely area of the AMBER system where differences may be perceived is the kneepad area, due to the addition of the multiple layered protective kneepad composite system. This is a known tradeoff for the system that results in enhanced protection in targeted areas such as the knee.

Subjective Wear Trial

Wear trials are traditionally executed to gather subjective and/or objective data. Due to the fact that the AMBER garments were already thoroughly objectively tested through sweating manikin testing and fabric level evaluation, an important and vital subjective comparison between the AMBER prototype and the baseline market garments was needed to assess real user responses on comfort, usability, functionality, and practicality.

Wear Trial Objectives

The objectives of the AMBER wear trial were related specifically to the perceived comfort and functionality of the garment system. Comfort is a metric comprised of the interactions between textiles and garment design, the physiological and psychological responses of the wearer, and the climatic conditions of garment wear. Fabric tactile comfort is associated with both the physical properties of the fibers and fabric construction as well as the thermal and moisture properties. The combined effect of these properties on wearer perceptions of comfort can only be determined through subjective evaluation. A wear test to compare the perceived comfort of the AMBER garment against the selected baseline garments was designed. City of Raleigh, NC Fire Department firefighters, used as human subjects, performed a specified set of activities within an environmentally controlled chamber. Nineteen (19) of the twenty (20) participants recruited for the performance evaluation completed all three wear sessions. One garment system was worn per session.

Figure 11: Baselines on participants: Baseline 2: 100% Nomex® IIIA (all blue) and Baseline 1: 100% cotton shirt and pants (white shirt/blue pant)

Protocol

Test methodology was designed to allow participant evaluation of comfort while wearing selected trial garments during periods of physical activity and rest. Specific exercises were included to target certain areas of the body for an assessment of design integrated protective features and functionality. The protocol consisted of twelve periods: seven (7) rest and five (5) exercise. The first two periods were rest periods, one outside and one inside the environmental chamber (25°C, 50% RH) during which participants recorded their initial impressions of the garment. Each subsequent exercise period was followed by another period of rest in which they again assessed the perceived comfort of the area (legs and knees, upper body movement, full body engagement tasks) being evaluated. A questionnaire was used to record subjective ratings, as well as specific feedback related to overall mobility, garment system form, and user acceptability.

The protocol of activities with testing periods is found in Table 21 below:

Table 21: AMBER human subject evaluation protocol

Test Period (rating)	Time (minutes)	Activity	Temperature °C (°F)	Relative Humidity (%)
1	30	Sitting at rest	~ 21 (70)	~ 50
2	10	Sitting at rest in environmental chamber	~ 25 (77)	~ 50
3	6	Warm-up/stretch exercise	~ 25 (77)	~ 50
		T-25 Cardio Alpha-1		
4	10	Rest	~ 25 (77)	~ 50
5	6	Leg and knee tasks	~ 25 (77)	~ 50
		Static one side kneeling (1 min) Both sides kneeling and pegboard task (2 min) Dynamic kneeling and standing (1 min) Step-ups (2 min)		
6	10	Rest	~ 25 (77)	~ 50
7	5	Upper stretch movements	~ 25 (77)	~ 50

Test Period (rating)	Time (minutes)	Activity	Temperature °C (°F)	Relative Humidity (%)
		Torso twists Toe touches Arm wraps Extended arms		
8	10	Rest	~ 25 (77)	~ 50
9	5	Full body engagement tasks	~ 25 (77)	~ 50
		Squats and twists Side leg lifts Jumping jacks Elbow to knees		
10	10	Rest	~ 25 (77)	~ 50
11	5	Turnout suit donning/doffing	~ 21 (70)	~ 50
12	15	Rest	~ 21 (70)	~ 50
Total testing time	**122**			

Participants were also asked to perform a timed donning and doffing of a turnout suit with the AMBER garment to ensure modularity with existing PPE. Finally, each participant scheduled a separate session in which each blindly evaluated each of the three uniforms. Since fit and form are such a critical aspect of perceived comfort, it is important to note that all subjects participated in a fit session prior to the wear trial.

The questionnaire that each participant filled out for each test period was designed to evaluate user perception of the garments based on both a set of negative descriptors representing specific physical properties and four specific parameters. The four parameters were: comfort, breathability, softness, and moisture sensation. The overall moisture sensation and comfort were evaluated at specific locations within the garments such as the collar, underarms, back, front, waist, seat, and legs. After each period of exercise, the participants were asked to rate the garment (by location and by component), on a bipolar one-to-seven (1-7) scale (where seven is considered the best). This was followed by a question asking the participants the degree to which they were aware of each of the negative descriptors on a scale from 1-5. A list of negative descriptors and their associated physical properties is shown below in Table 22. Negative descriptors were used because it has been determined that an individual is more likely to be able to discern differences in levels of unpleasantness than pleasantness. Additional details on the wear testing can be found APPENDIX I: Human Subject Evaluation documentation.

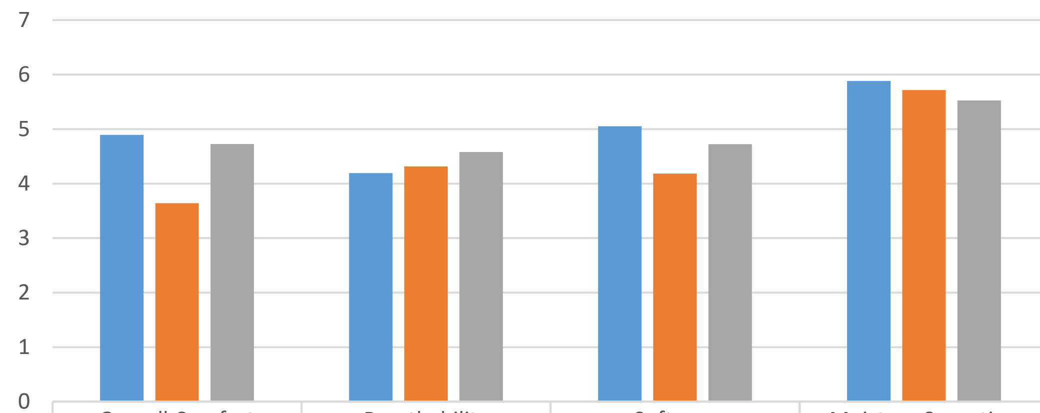
Table 22: Negative descriptors and their associated physical properties

Negative Descriptors	Associated Physical Property
Tight	Garment Fit
Non-breathable (hot)	Moisture Permeability/ coolness from sweat evaporation
Heavy	Fabric Weight
Stiff	Bending Rigidity
Sticky	Moisture Vapor Absorption
Non-absorbent	Liquid Moisture Management
Damp	Liquid Moisture Absorption
Clingy	Moisture and Surface
Non-stretchy	Tensile Extensibility

Negative Descriptors	Associated Physical Property
Inflexible	Bending Rigidity
Rough	Fabric Hand and Surface

Results

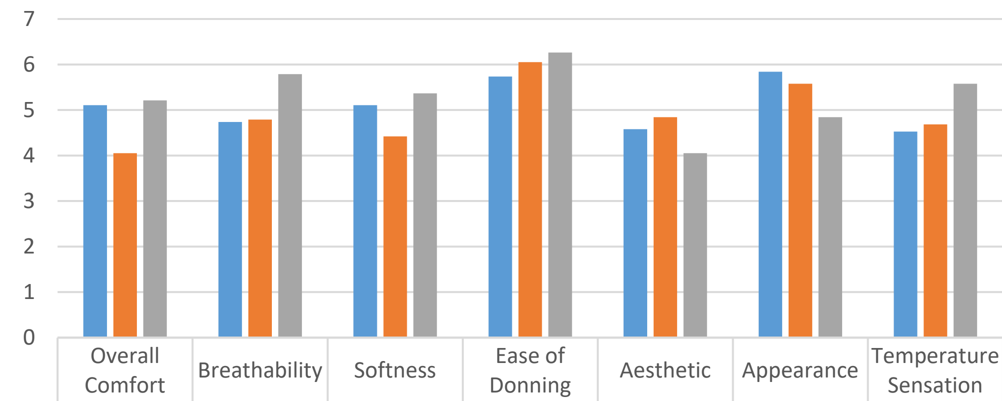
Figure 12 below represents the combined average rating of each wear trial garment system A-C (A: Cotton baseline, B: Nomex®IIIA baseline, C: AMBER prototype) across the four parameters evaluated in the tests on the scale of 1-7: overall comfort, breathability, softness, and moisture sensation.



	Overall Comfort	Breathability	Softness	Moisture Sensation
A	4.89	4.19	5.05	5.88
B	3.64	4.32	4.18	5.72
C	4.73	4.58	4.72	5.53

Figure 12: Combined average rating of each garment system on scale of 1-7 (higher score indicates best user-perceived wear comfort)

Figure 13 represents the garment rankings across the parameters that were evaluated upon donning and prior to entry of the environmental chamber.



	Overall Comfort	Breathability	Softness	Ease of Donning	Aesthetic	Appearance	Temperature Sensation
A	5.11	4.74	5.11	5.74	4.58	5.84	4.53
B	4.05	4.79	4.42	6.05	4.84	5.58	4.68
C	5.21	5.79	5.37	6.26	4.05	4.84	5.58

Figure 13: Average rating of each garment at donning on scale of 1-7 (higher score indicates best user-perceived wear comfort)

From the above data, the AMBER prototype performed as well or better than either of the baseline garments tested in the wear trial in all categories except for aesthetic, appearance, and moisture sensation. These results were expected. The AMBER system is designed to push the envelope of protection, performance, and comfort while striving to maintain a degree of professionalism desirable by the first responder community. Since these parameters usually correlate negatively to one another some trade-offs were noted and expected. The baselines that the AMBER system was tested against in this wear trial (cotton and Nomex) are not treated in any way to repel liquid contaminants as the AMBER garment is. It is understood that the application of any repellent finish has the tendency to reduce the comfort on "perceived moisture sensation" of a fabric due to the changing physical features of impregnating a solid into a textile.

The negative descriptor rating system was used at each of the evaluation periods of the wear trial. Such a method allowed the targeted areas to be assessed as the level of activity, exertion, and sweat production increased. The AMBER prototype shirt was perceived to be as or more comfortable across the timeline of the wear trial than the competing baselines. A paired t-test analysis (determined whether the differences in means were statistically significant) was performed and some of the results are shown below. In Table 23 the comparison is listed so the first garment system is the one expected to perform better than its counterpart is (A vs B in overall comfort; A is significantly better at the 90% confidence level). This data, along with the wear trial feedback from the participants, highlighted areas for improvement (kneepad location and aesthetics, fastening and closure methods, and fit) that were modified in the final design iterations. Additional information on the wear testing data can be found in APPENDIX J: Human Subject Evaluation data.

Table 23: Statistical analysis of AMBER wear trial comparisons

	Overall Comfort	Donning Breath-ability	Softness	Moisture Sensation	Tight	Heavy	Stiff	Rough	Stretch	Flexibility
A vs B	*	N	N	N	*	***(-)	N	N	***	N
C vs A	N	***	N	N	***	N	N	N	***	*
C vs B	**	**	**	N	***	**	*	**	***	**

**** = Significant @ 99% level* *** = Significant @ 95% level*
** = Significant @ 90% level* *N = Not significant*
(-) = Reverse comparison (B vs A, since in this case B was significantly better than A)

NFPA 1975 Certification

As a deliverable from the overall AMBER project, the AMBER prototype systems were required to be certified to the NFPA 1975 standard. For NFPA 1975 certification, the overall system can be certified based on a series of material and system level evaluations. Per the requirements of NFPA 1975, the AMBER prototype systems were certified to the NFPA 1975 standard by Underwriters Laboratory. See Table 24 for the technical testing criteria and the standard for additional details on system level and design criteria needed for NFPA 1975 certification (5).

Table 24: NFPA 1975 Certification Requirements

NFPA 1975 MATERIAL PERFORMANCE REQUIREMENTS				
Property		**Unit of Measure**	**Limits**	**Test Method**
NFPA 1975 Certification Requirements				
Seam Strength	*	lbf (pound force)	30	ASTM D1683 per NFPA 1975
Heat and Thermal Shrinkage	*	% shrinkage (any direction)	<10	ASTM F2894 per NFPA 1975
Thermal Stability	*	resistance to blocking rating	1 or 2	ASTM D751 per NFPA 1975
Thermal Stability	*	melt, ignite, stick to the glass plate	no, no, no	ASTM D751 per NFPA 1975
Label Durability	*	legibility	legible	AATCC 135 (25 laundry cycles)-Legibility per NFPA 1975
Thread Heat Resistance	*	Melting Temperature (°C)	>260	NFPA 1975, Procedure 8.7 per NFPA 1975
Char Length	**	Inches (mm)	<6 (190)	ASTM D6413 per NFPA 1975 if required
After Flame	**	seconds	<2	ASTM D6413 per NFPA 1975 if required
Melt/Drip	**	yes/no	no	ASTM D6413 per NFPA 1975 if required
Liquid Resistant (impact penetration)	**	% penetration	≤15	AATCC 42 per NFPA 1975 if required

NFPA 1975 MATERIAL PERFORMANCE REQUIREMENTS				
Property		**Unit of Measure**	**Limits**	**Test Method**
NFPA 1975 Certification Requirements				
Odor resistance (antimicrobial)	**	% reduction in 1 hour	≥99	AATCC 100 per NFPA 1975 if required
* **Base Certification**	**Note1:** Requirements taken from NFPA 1975. Requirements apply to all materials as specified during certification from the certification body. May not apply to all support materials.			
** **Optional Certification**	**Note2:** While the AMBER garments are estimated to meet the optional requirements based on internal testing during development, the current NFPA certification only covers the baseline requirements for NFPA 1975.			

Conclusions

Coupled with the data from the human wear testing and the open user feedback, the final design of AMBER was optimized, amended, and finalized for the final production of 150 prototype garment ensembles, achieving the overall program objectives as defined by DHS. AMBER provides DHS with a multi-hazard limited protection daily wear ensemble that can be used across multiple first responder duties. While the AMBER garment system does provide enhanced protection over baseline uniform systems (Flame Resistance, localized cut and impact protection, and liquid resistance), it is still not intended to be worn as a primary protective garment, as the overall system protection is limited when compared to primary protective systems (i.e. turnout suit or hazmat suit). It is important that the limited nature of the enhanced protection provided by the AMBER garments be effectively communicated to end users so that they clearly understand the limitations of the protection provided. This project developed a User Information Package that contains additional information for a user when evaluating the appropriate use of the AMBER system in their duties (APPENDIX K: AMBER User Information Package).

During the limited user testing that has been conducted to date, overall user acceptability for the developed AMBER system has been positive and is comparable to the baseline garments for comfort, but has a higher protection element than what is currently available with the baseline garments. The AMBER garment system is certified to the NFPA 1975 Standard - 2014 edition, and Protect the Force (PTF) has produced and delivered 150 certified prototypes to DHS S&T for follow-on operational wear testing. PTF is currently planning for the commercial launch of the AMBER system after completion of the wear testing. Any changes required after the wear testing are planned for implementation prior to commercialization. NC State and PTF are pursuing a joint Patent application for the AMBER system(s) and elements, and are currently negotiating terms for a licensing agreement for use of the AMBER technology.

APPENDIX A: Background

The Project Responder 3 (PR3) Report has identified a priority need for clothing and equipment to protect against "all hazards in an unpredictable response environment" [(1)]. Additionally, Project Responder 4 (PR4) builds on this priority need by creating a related capability need statement within the Responder health, safety and performance domain to indicate that protective clothing and equipment is needed for responders that protects against multiple hazards [(2)].

As demonstrated in Table 25, the solutions that are identified for this project are in strategic alignment with the overall DHS S&T mission and are directly related to the below Research Technology Objectives (RTO) identified in Project Responder 4.

Related RTO's identified from PR4:

- Duty uniform with limited protection across threat spectrum
- Modular mission-specific protective layers
- Multi-threat performance and testing standards for a modular PPE system

Table 25: Strategic Alignment

Document	Alignment
DHS Quadrennial Homeland Security Review (6)	Directly supports the mission to Strengthen National Preparedness and Resilience
S&T Strategic Goal Alignment (7)	1. Rapidly develop and deliver knowledge, analyses, and innovative solutions that advance the mission of the Department and 3. Strengthen the Homeland Security Enterprise and first responders' capabilities to protect the homeland and respond to disasters
FRG Priority Capability Gaps (2) (7)	PR 4 Capability Domain: Responder health, safety, and performance PR 4 Capability Statement: Protective clothing and equipment for all responders that protects against multiple hazards PR 4 Applicable Response Technology Objectives (RTO) identified: • Duty Uniform with Limited Protection Across Threat Spectrum • Modular Mission-specific Protective Layers • Multi-threat Performance and Testing Standards for a Modular PPE System

The goal of this project was to provide a solution that addresses the needs as indicated in PR3 and PR4 reports and directly supports narrowing the gaps associated with current first responder daily wear uniform comfort and protection.

End Users

As identified in PR3 and PR4, the end users for this project are members of the First Responders community such as firefighters, law enforcement, and emergency medical services.

Firefighters

According to the NFPA's 2016 reporting, there are 1,160,450 firefighters in the United States. At 346,150 (just under a third of the total firefighter population), professional firefighters are present in almost every metropolitan area across the country. In addition, volunteer firefighters, numbering approximately 788,250 are available in even more localities, including rural areas, than professional firefighters [8].

Fires are an ever-present danger, whether due to human error, technical mishaps, or forces of nature. The modern fire service was developed to protect the population and their property from this danger at all times so there must always be firefighters available to heed the call and respond. Accomplishing that is no easy task. According to the Bureau of Labor Statistics [9], professional firefighters typically work extremely long, demanding, and varied hours. While some work shifts where they are on call for 10 hours followed by 14 hours off call, most firefighters work full day 24-hour shifts followed by two days off. During those 24 hour shifts, the firefighters are expected to remain on station unless they are called away. They are also expected to keep their base station wear uniform on at all times until their shift has ended. There are approximately 27,000 registered fire departments [10] in the United States, from Florida to Alaska, from hot and humid weather to cold and dry climates. Despite these differences, many firefighters wear the same base station wear uniform, with small variations to help in more extreme environments. Daily station wear uniforms are normally worn underneath firefighter's primary protective turn-out gear, which is heat protective. Firefighters also have a multitude of tasks to attend to while at the station that keeps them active that attribute to the general wear and tear on their station uniforms as well.

Law Enforcement

Law Enforcement (LE) personnel are tasked with enforcing the law, investigating crimes, responding to emergencies. Similar to other first responders, daily operations can vary depending on the type of job. LE consists of jobs such as police officers, detectives and criminal investigators that are found from the federal level [e.g. the Federal Bureau of Investigation (FBI), Federal Protective Service (FPS), Immigration and Custom Enforcement – Homeland Security Investigations (ICE-HSI), etc.] down to the county or local level (e.g. Sheriff). For the purposes of this project, as it is a uniform development project, Law Enforcement will refer to those personnel or job duties who would wear a uniform as part of their normal duties.

According to the Bureau of Labor Statistics [11], typical uniformed law enforcement personnel duties may include but are not limited to: responding to emergencies, patrolling assigned areas, conducting traffic stops, issue citations, pursue and apprehend people who break the law, investigate suspicious activities, conduct personnel, vehicle and building searches, and special and tactical operation. The daily activities of police "can be physically demanding, stressful and dangerous". They regularly work at crime and accident scenes, work in all environmental conditions, and routinely deal with the hazards they encounter in these types of situations. "Police and sheriff's patrol officers have one of the highest rates of injuries and illnesses of all occupations. They may face physical injuries during conflicts with criminals and motor-vehicle pursuits or when exposed to other high-risk situations" [11].

One of the unique hazards for police officers is their need for ballistic protection. Protection from ballistics is not typically a high priority for firefighters or Emergency Medical Services (EMS). Ballistic protection, similar to flame protection, generally requires a compromise in comfort and usability.

Emergency Medical Services

Emergency Medical Services (EMS) provide emergency medical care out-of-hospital and transportation of patients to care facilities. The overarching goal is to provide treatment to those in need of immediate medical attention. Their secondary purpose is that of medical transportation. Should a patient need additional medical attention the emergency medical service will transport these patients as required. In many large cities in the United States, the EMS is a separate agency from the fire department. In these situations, the daily wear uniform is provided by the EMS department and does not include the same requirements as the fire department's daily wear uniform. This uniform is traditionally cotton or polyester/cotton cargo pants with large pockets for carrying extraneous gear that needs to be easily accessible for the responder in an emergency, and a department-issued shirt or jacket. In the research performed for this project, the EMS responders polled were concerned with looking professional and having as much functionality within their uniform as possible while still remaining comfortable.

In smaller municipalities, the fire department and the emergency medical service personnel can be from the same department [(8)]. In these cases, the fire department requires that some of their firefighters are also trained medical technicians who respond along with the other firefighters. The daily wear uniform for these responders is traditionally the same as the firefighters they are responding with.

While the EMS (when separate from the fire department) does not necessarily respond to the range of calls that the fire department does, there is the possibility of injury or health problems any time they respond. This can include accidents, fires, and other health concerns. Just like firefighters, the nature of these calls puts the EMS responders in contact with many potential hazardous substances, such as chemicals, liquids (blood, water, etc.), and other potential physical hazards [(8)]. Since many of the people the responders treat will be laying or sitting down, they will often find themselves kneeling for long periods on uneven and harmful surfaces, which can damage their clothes and contact their skin through direct contact, abrasion, or penetration of harmful liquids through their clothing.

APPENDIX B: Requirements Development

One of the key avenues of success during AMBER development was the requirements development process, where system performance requirements were traced directly to user needs. The Requirements Development process, translating user needs into measurable requirements, provided the foundation for building a system focused on meeting the needs of the end users.

Performance Goals

T-PACC translated the KPPs and Key System Needs into performance goal statements that start to add quantifiable metrics to need descriptions, helping describe how each need can be measured.

System Goals:

- Comfort Goal
    - To be comfortably worn by male and female firefighting (FF), emergency medical services (EMS) and law enforcement (LE) personnel on a daily basis in the station and in the field (24-hour shifts ~3 times a week or ~10 times a month)
- Durability Goal
    - To physically and visually hold up over a period of 8 months (~35 launderings, ~1248 hours wear)
- Usability/Practicality Goal
    - To be functional for FF, EMS, and LE personnel, it can be worn underneath turnout gear, ballistic vests and Hazmat suits. It can be customized per department policy and considers future integration.
- Aesthetics Goal
    - To be professional, recognizable to the public and other responders, and have a desirable style to users: “cool factor”, “high speed, low drag”.
- NFPA 1975 Certification Goal
    - To be certified to NFPA 1975 requirements
- Enhanced Protection Goal
    - To be certified to NFPA 1975 flame resistance and water resistance optional requirements
- User Acceptability Goal
    - To be acceptable to the user community of FF, EMS, and LE personnel
- Reasonable Cost Goal
    - To be at a cost within the current market range for normal duty uniform garments.
- Multi-Service Applicability Goal
    - Applicable to FF, EMS, and LE personnel
- Optional Tradeoff Protection Goal
    - Limited Heat Protection
    - Limited Splash Protection
    - Limited Puncture protection
    - Limited anti-microbial behavior
    - Localized impact protection
    - Electrostatic discharge
    - Environmental Protection

Requirements

The main requirement parameters and appropriate test methods that were determined for each key need are shown in the Table below by category.

Note: Functionality/Usability will be determined by user function testing.

Table 26: Key Needs linked to performance parameters and test methods

Key Need Category	Parameter	Test Method
User Comfort	System weight	N/A
User Comfort	System Total Heat Loss	ASTM F1291 and ASTM F2370
User Comfort	Fabric weight	ASTM D3776
User Comfort	Air Permeability	ASTM D737
User Comfort	Drape (Shear Stiffness)	Kawabata Evaluation System
User Comfort	Stiffness (Bending Rigidity)	Kawabata Evaluation System
User Comfort	Fabric Total Heat Loss	ATM F1868
User Comfort	Stretch and Recovery	Modified ASTM D 4964
User Comfort	Fabric weight	ASTM D3776
User Comfort	Fabric Thickness	ASTM D1777
User Comfort	Moisture Vapor Transmission	MVTR (upright cup method)
NFPA 1975 Certification	Seam Strength	ASTM D1683 per NFPA 1975
NFPA 1975 Certification	Heat and Thermal Shrinkage	ASTM F2894 per NFPA 1975
NFPA 1975 Certification	Thermal Stability	ASTM 751 per NFPA 1975
NFPA 1975 Certification	Label Durability	AATCC 135 (25 Laundry) per NFPA 1975
NFPA 1975 Certification	Thread Heat Resistance	NFPA 1975, procedure 8.7
NFPA 1975 Certification	Char Length	ASTM D6413 per NFPA 1975
NFPA 1975 Certification	Afterflame	ASTM D6413 per NFPA 1975
NFPA 1975 Certification	Melt/drip	ASTM D6413 per NFPA 1975
Durability for Daily Wear	Breaking Strength	ASTM D5034
Durability for Daily Wear	Tear Strength	ASTM D1424
Durability for Daily Wear	Colorfastness to Laundering	AATCC 135
Durability for Daily Wear	Colorfastness to Crocking	AATCC 8
Durability for Daily Wear	Colorfastness to Perspiration	AATCC 15
Durability for Daily Wear	Colorfastness to Light	AATCC 16
Durability for Daily Wear	Abrasion	ASTM D4966
Durability for Daily Wear	Burst Strength	ASTM D3787
Aesthetics	Resistance to Pilling	ASTM D3512
Aesthetics	Appearance	AATCC 143
Enhanced Protection	Liquid Resistance	ISO 6530
Enhanced Protection	Liquid Resistance	AATCC 118
Enhanced Protection	Liquid Resistance	AATCC 42 per NFPA 1975
Enhanced Protection	Odor Resistance	AATCC 100 per NFPA 1975
Optional Tradeoff Protection	Puncture	ASTM F1342
Optional Tradeoff Protection	Manikin Flash Fire Body Burn	ASTM F1930 per NFPA 2112
Optional Tradeoff Protection	Viral Penetration	ASTM F1671 per NFPA 1971
Optional Tradeoff Protection	Cut Resistance	ASTM F1790
Optional Tradeoff Protection	Impact Resistance	Ball Drop (.544kg weight, .5 m height)

APPENDIX C: Concept Development

The first and most important stage during concept development was the Concept Development Workshop (CDW). The CDW was critical in creating the initial concepts (Figure 14), which became the first iterations of AMBER, known as the Technical Base Ensemble (TBE) and the Modernized Base Ensemble (MBE) (Figure 15 and Figure 16). The TBE and MBE were later changed to reflect feedback from DHS.

Concept Development Workshop (CDW)

The purpose of this two-day workshop was to "brainstorm" all areas related to protective technologies, materials, and design with a focus on the requirements specified for AMBER. AMBER KPPs and Project Responder reports were presented as well as a briefing on baseline garments in order to provide background and context for the project. A multidisciplinary team from NC State University, TPACC, and PTF participated in the workshop.

The CDW agenda assigned participants into specific breakout groups; groups were formed with differing areas of knowledge and expertise to ensure thoughtful and innovative thinking. Each group was tasked with designing a "revolutionary" and "evolutionary" design for AMBER. Revolutionary is defined as being something truly out of the box with user acceptability on a lower priority. Evolutionary is defined as a design that encompasses elements that are recognizable among the user group, with innovativeness being the forefront of the design.

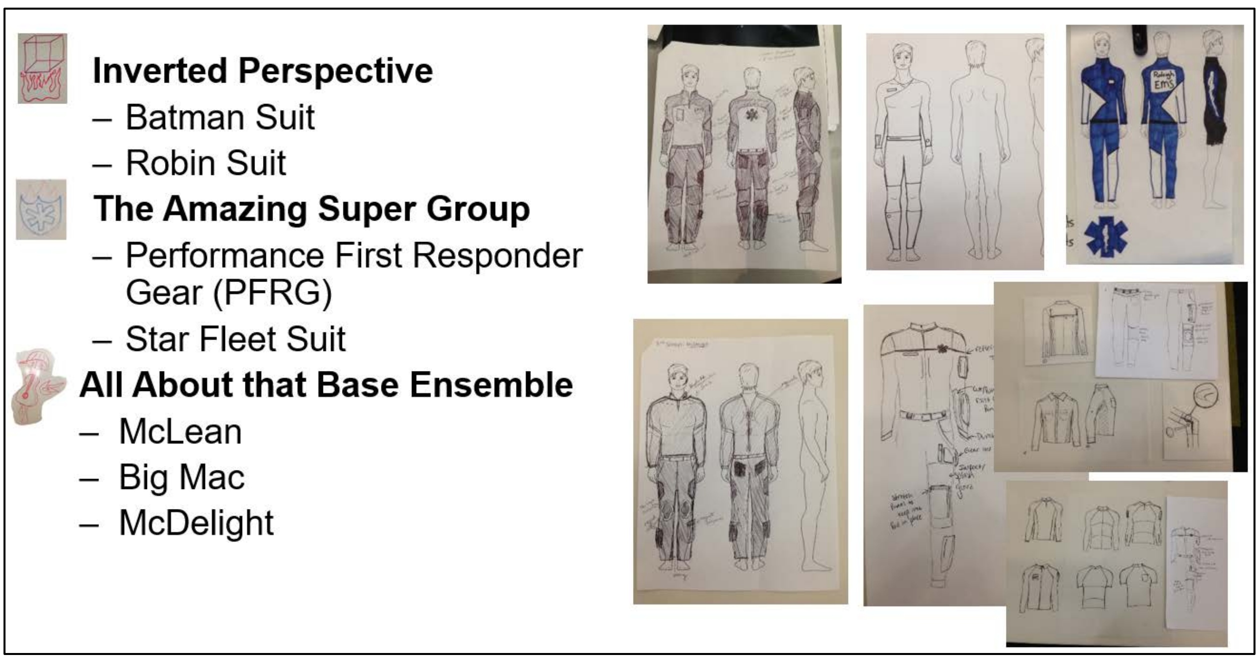


Figure 14: CDW groups' concepts for presentation

Outputs from the CDW included material options, functional design options, integrated protective features as well overall design aesthetics. Group concepts were then presented to the entire workshop audience, with certain features of each concept being assigned a value of originality, necessity, and practicality. These values were then entered into a down-selection process using a tool to help define its overall weight of importance and potential trade-off to the concept. The final result was four leading design/features that were then integrated into two specific concepts – with the intent of each concept catering to a set number of protective and comfort trade-offs. TBE and MBE were both further refined with conceptual sketches and served as AMBER's first iteration, which was then taken to the users and focus group for additional and valuable critical feedback to ensure development was on track towards acceptability.

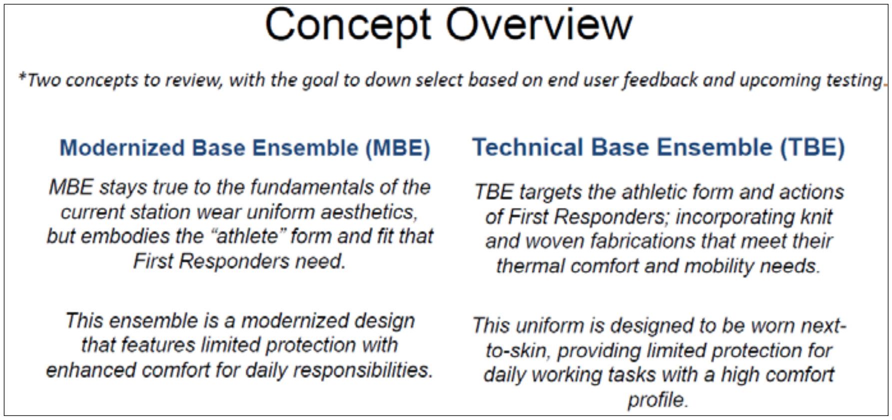


Figure 15: MBE and TBE concept statements presented to DHS – FRG

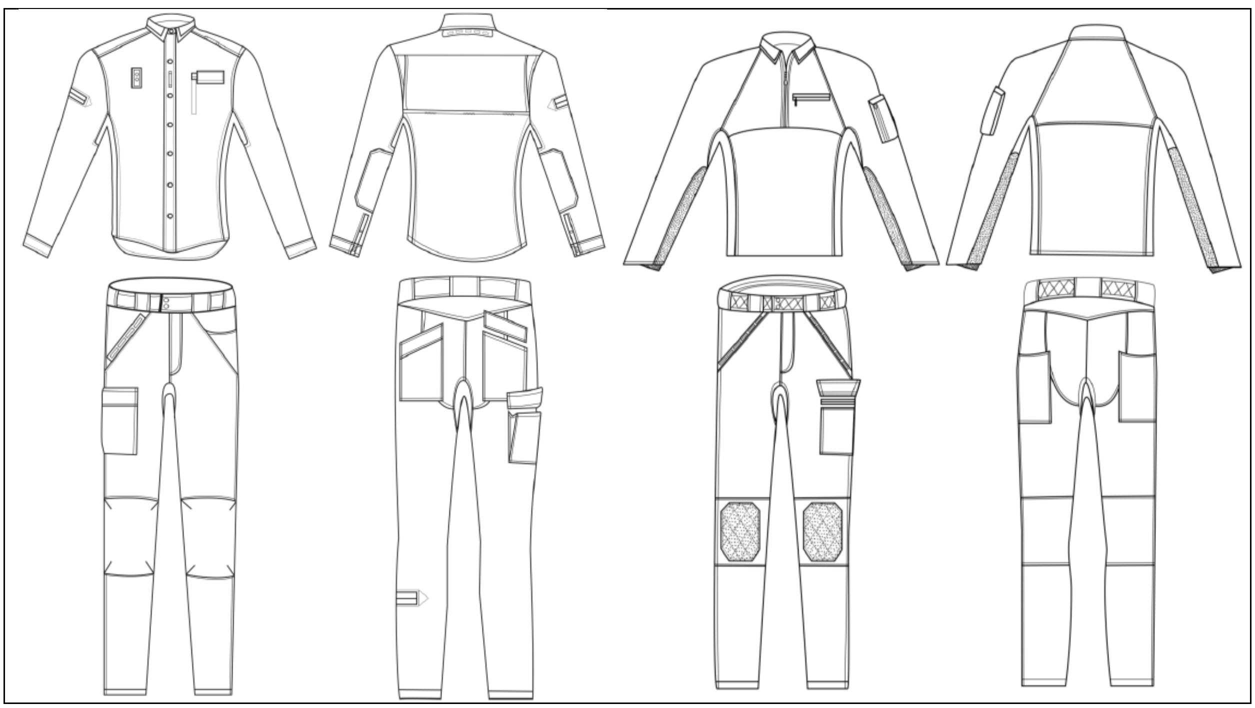


Figure 16: MBE (right) and TBE (left) concept sketches presented to DHS – FRG

DHS expressed concerns that the concepts developed did not provide enhanced protection over currently available garments and did not meet the goals of the SOO. While these first concepts were highly focused on comfort, and provided limited protection against some of the desired threats, DHS requested that the concepts provide enhanced protection over existing garments. NC State took the original concepts and along with PTF modified them to put a higher priority on the protection aspects of the concept. The importance of retaining comfort and wearability was still a high priority, however, the team now allowed for more comfort/wearability tradeoffs for additional protection.

The team then developed the second set of concepts, which were titled the Multi-hazard Base Ensemble (MBE) Level 1 and level 2. MBE Level I was designed to provide limited protective performance combining advanced protective materials and innovative design elements with comfort features for prolonged daily wear. This base uniform system incorporates elements of multi-hazard protection with minimum impact on wear comfort. MBE Level II was designed to offer a heightened level of limited multi-hazard protection incorporating cutting-edge high-performing materials, technologies, and innovative design features. This concept design prioritizes the protective elements of the uniform.

These two concepts were then used as the basis for presenting and gaining feedback from the FRRG.

FRRG Feedback

A critical next step of the concept development process was the inclusion of user feedback of iterations of design and technology. This served of great importance as it allowed for open communication and dialogue amongst the researchers, end users, and project sponsors, which increases the likelihood of success for wide user acceptability for the marketplace.

User groups that participated in feedback sessions for the duration of the AMBER project included the DHS First Responder Resource Group (FRRG), Raleigh Fire Department (RFD), as well as the North Carolina State University Police Department (NC State PD). Group sessions were held on a volunteer basis only and participants were not compensated in any form.

In each in-person feedback session, the applicable AMBER iteration at the time was presented and thoroughly discussed, covering all aspects of design, functional features, and protective capabilities. Participants were arranged in a roundtable setting and were prompted to speak on any aspects of AMBER. Their comments were recorded and noted during discussions. The result of frequent user feedback was the ability to make practical and astute improvements quickly when necessary. For example, to add durability and abrasion resistance to the shirtsleeve, adding Superfabric® was thought to be a potential solution (Figure 17). However, in practice and after a few participants donned the shirt, it was quickly apparent how the harsh hand was affecting the wearer comfort and the trade-off for comfort around the wrist to the protective element was not balanced. Within the group, it was noted that no participants would consider wearing a station wear shirt with the Superfabric® on the sleeves.

Figure 17: Superfabric® implemented in first iteration (left) and final cuff design (right)

Concept Refinement

Utilizing user feedback over design iterations as well as assessing a testing matrix for different material integrations, the MBE Level 1 and MBE Level 2 were refined. These refinements closely resemble the final certified design. The below figures illustrate the evolution of AMBER as it was refined over the project timeline to the iteration that was used during the human subject system evaluation. The differences between the wear trial ensemble and the concept renderings are the exclusion of the Superfabric® on the sleeve cuff, the shape of the kneepad, as well as the reflective trim. The wear trial garment can be viewed in Figure 1 and Figure 9 earlier in this report.

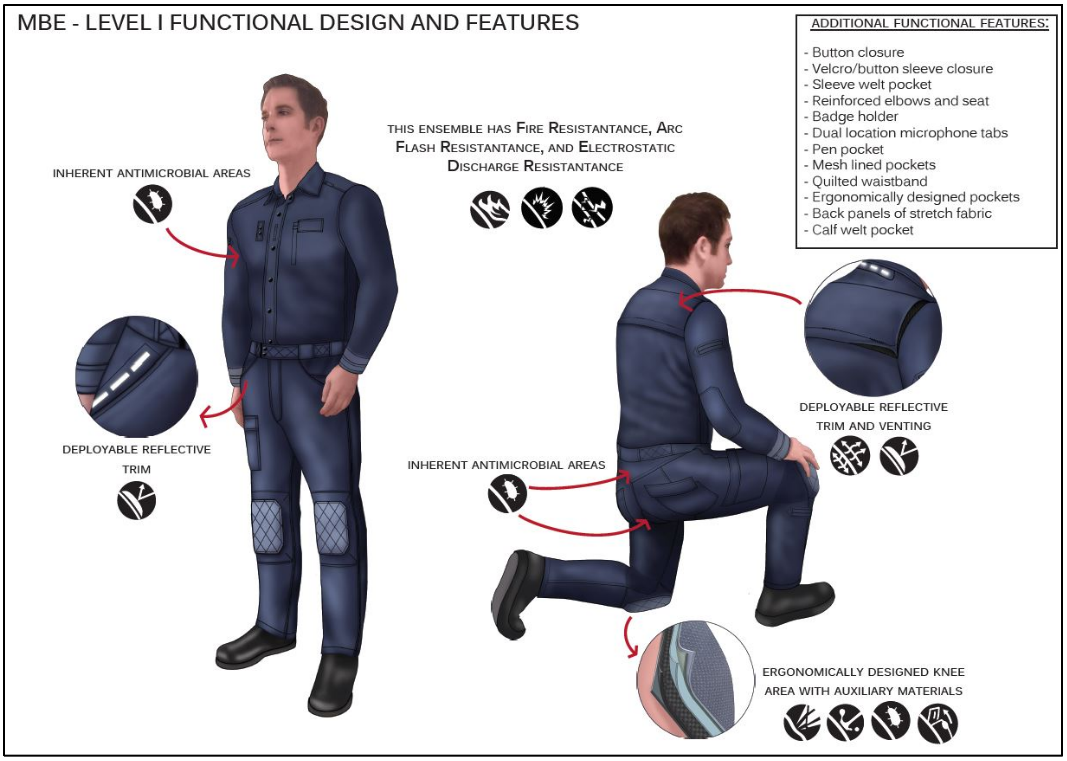


Figure 18: MBE Concept Level I ensemble for refinement for system evaluation

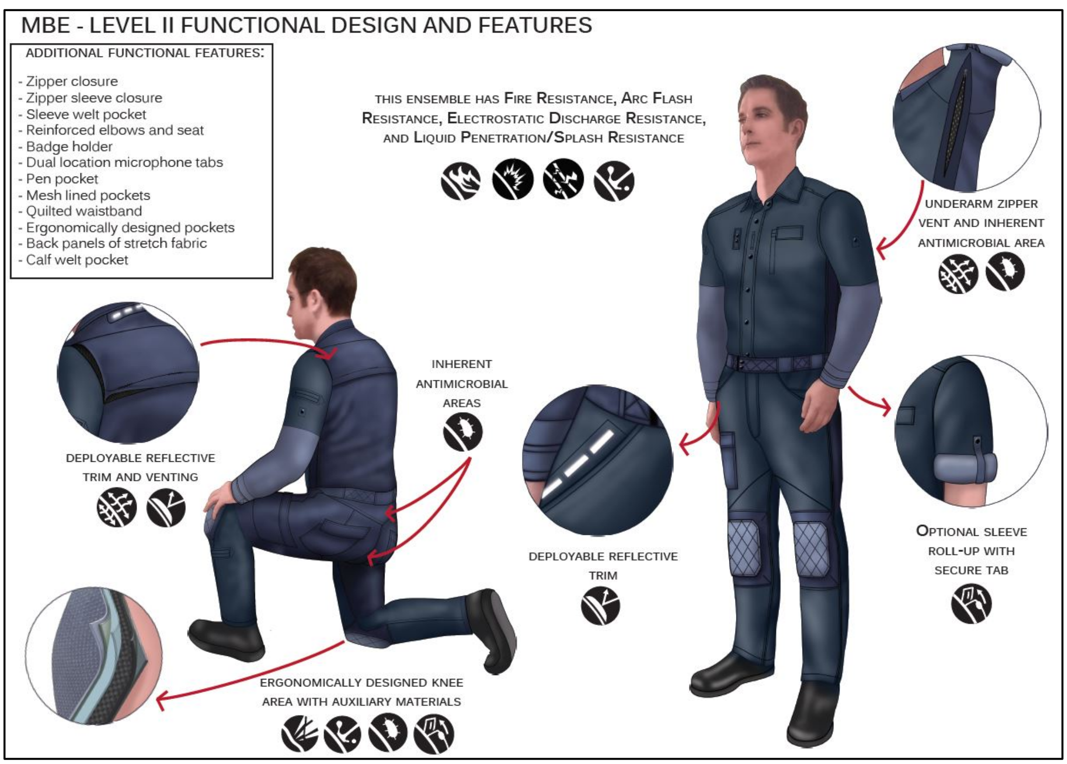


Figure 19: MBE Concept Level II ensemble

APPENDIX D: Material Selection Methods

Sourcing

After concepts were developed and the types of fabrics required for each concept were known, a rigorous material sourcing effort proceeded. There were three main areas of material sourcing conducted based on the concepts from the workshop: woven pant/shirt (Type 1), stretch panel performance knits (Type 2), and a membrane/laminate technology (Type 3). An extensive search was conducted for each type of material within the marketplace, with over 50 materials being reviewed. T-PACC attended several materials and protective clothing based trade shows, contacted military and workwear fabric suppliers, and looked through T-PACC's database of materials used in past T-PACC PPE projects. The initial material search focused on materials used in similar industries, such as military and workwear industries. The Type 1 materials selected were generally Flame Resistant (FR), available in a Navy color, and within the 5 - 8.0 oz/yd^2 weight range. Similarly, the Type 2 materials were generally Flame Resistant, highly air permeable, moisture wicking, available in a Navy color, and within the 5 - 7.0 oz/yd^2 weight range. Lastly, the search for laminate materials that were thin and comfortable and still provided some chemical protection didn't turn up suitable commercial materials for daily wear, so it was decided to create a tri-laminate fabric in-house using a combination of the woven, knit and membrane technologies researched. Therefore, the Type 3 materials (membrane/laminate) were chosen based on their ability to pass the liquid, water and viral penetration tests from NFPA 1971, their ability to be flexible as a laminate, their Moisture Vapor Transmission Rate (MVTR), and their oil resistance.

After the initial evaluation of the sourced materials, a smaller set of materials were selected during a series of material selection meetings held jointly between T-PACC and PTF. Each material selected was done so for additional evaluation via performance testing during Phase I. Table 27 - Table 30 below show the initial materials selected for Phase I testing in each category.

Table 27: Type 1 (woven) material options for testing

Manufacturer	Style Number	Weight (oz/yd^2)	Thickness (mm)	Fabrication	Fiber
TenCate	Tecasafe® 580A	6.2	0.53	Twill	Modacrylic, Cellulose, Aramid
TenCate	Tecasafe® 700A	7.9	0.63	Twill	Modacrylic, Cellulose, Aramid
TenCate	Tecasafe® 700	7.3	0.56	Twill	Modacrylic, Cellulose, Aramid
TenCate	Tecasafe® 850A	8.6	0.67	Twill	Modacrylic, Cellulose, Aramid
PBI Performance Products, Inc.	TriGuard 4.5 Twill	4.8	0.36	Twill	50% Twaron, 30% FR Viscose, 20% PBI
PBI Performance Products, Inc.	TriGuard 5.3 Ripstop	5.3	0.39	Ripstop	50% Twaron, 30% FR Viscose, 20% PBI
Milliken	ResQ™ 846008	6.0	0.53	Plain Weave	Nomex IIIA
Milliken	ResQ™ 847351	5.9	0.43	Twill	37/33/30 Aramid/Synthetic/Cellulose
Milliken	ResQ™ 846900	5.6	0.34	Twill	37/33/30 Aramid/Synthetic/Cellulose

Table 28: Type 2 (knit) material options for testing

Manufacturer	Style Number	Weight (oz/yd^2)	Thickness (mm)	Fabrication	Fiber
Polartec®	2012	5.2	0.69	Jersey/Mesh	72% Modacrylic, 28% Rayon
Polartec®	2014	5.0	0.52	Jersey	68% Modacrylic, 29% Rayon, 3% Spandex
Massif®	Battleskin	7.0	0.50	Jersey	36% Nylon, 30.5% MetaAramid, 30.5% Modacrylic, 3% Spandex
Massif®	Helium	6.4	0.47	Jersey	94% Cotton, 6% Spandex
Massif®	Blaze	7.2	0.50	Jersey	93% Cotton, 7% Spandex
Massif®	Breeze	5.5	0.48	Pointelle Mesh	87% Cotton, 7% Polyester, 6% Spandex

Table 29: Type 3 (membrane) material options for testing

Membrane	Polymer	Weight (oz/yd^2)	Thickness (mm)
Porelle® P540FR	Polyurethane	1.6	0.04
Agrotec TX1540	Polyurethane	0.9	0.02
Agrotec TX4100	Polyurethane	0.5	0.01
°eVent®	Expanded PTFE	0.7	0.02
Porelle® P345	Polyurethane	1.6	0.12
Porelle® P55	Polyurethane	0.8	0.04

Table 30: Layering Options for initial tri-laminate prototypes

Shell Options	Membrane Options	Next to Skin Options
TenCate Tecasafe® Style 580A	Pil Membranes Porelle® Styles P540FR, P345, P55	Polartech® Powerdry® FR Style 2012 and 2014
PBI TriGuard Style 4.5 twill	Agrotec Style TX 1540, TX 4100	Massif Style Breeze
Milliken ResQ™ Style 84690	General Electric event® Style OQMO1165OT	Milliken Style PolyParadox FR
Massif® Blaze™		

Testing

All main materials selected for further testing each had desirable performance attributes and were thus potential options to be included in the AMBER system. Within each main performance category (i.e. Comfort, Durability, Protection), several key measures were selected for each material type to provide an initial indication of the fabric performance for that performance category. For example, User Comfort was identified as a KPP, so test methods with appropriate measures were chosen as representative of that User Comfort KPP. For comfort, a combination of thermal comfort (Total Heat Loss and air permeability) and sensorial comfort (stiffness and drape) were determined to be good measures that can differentiate the comfort performance of the materials being tested. In addition to key performance variables, the overall downselection process also included a cost metric (dollars per square yard). Cost is often not considered until closer to the end of the material downselection. However, for user acceptability and as a stakeholder requirement, the cost was included at the beginning of the material downselection process. Table 31 shows those test methods chosen for initial testing.

Table 31: Performance Characteristic and Test Methods used for the initial testing

Key Need Category	Performance Characteristic	Test Method	Units
General	Basis Weight	ASTM D 3776	oz/yd^2
General	Thickness	ASTM D 1777	mm
Durability	Abrasion	ASTM D 4966 (martindale)	Rubs to failure
Durability	Tear (wovens only)	ASTM D1424 Elmendorf Tear Average	lbf (N)-Average
Durability	Burst(knits only)	ASTM D3786 Mullens Burst or 3787 (Ball burst)	lbf (N)
Durability	Breaking	ASTM D5034 Tensile Strength Length (Average)	lbf (N)-Average
Durability	Pilling (Knits)	ASTM D 3512	Pill Rating
Durability	Laminate Bond Strength (initial)	ASTM D 2724 (Initial)	mN (ozf)
Comfort	Thermal Comfort	ASTM F 1868	W/m^2
Comfort	Stiffness	KES-Bending Rigidity	gf.cm2/cm
Comfort	Wicking	NCSU Vertical Wicking Test Method	Inch/min
Comfort	Drape	KES-Shear	gf/cm*degre e
Comfort	Air Permeability	ASTM D 737	$ft^3/min/ft^2$ (CFM)
Comfort	Moisture Vapor Transmission	Modified ASTM E96-80	g/cm^2-24 hours
Protection	Vertical Flame (Afterflame)	ASTM D 6413	seconds
Protection	Vertical Flame (Char Length)	ASTM D 6413	inches
Protection	Puncture	ASTM F 1342	lbf (N)
Protection	Liquid Resistance	AATCC 118	Rating Scale
Protection	Liquid Resistance*	ISO 6530	Percentage
*Water, 3% concentrate Aqueous Film-forming foam (AFFF), Battery Acid (37% by weight sulfuric acid to water), Fire-resistant hydraulic fluid, phosphate ester base, surrogate gasoline fuel C as defined in ASTM D 471 (50/50 % by volume toluene and iso-octane), Swimming pool chlorinating chemical (containing at least 65% free chlorine (saturated solution)			

Note: In addition to the variables listed in Table 31, cost (a stakeholder-defined variable) was also included as a variable during the downselection process.

Downselection

Methods

In order to effectively and efficiently downselect materials that could be used within the AMBER systems, T-PACC used a weighted properties method combined with a digital logic method to develop a decision-making tool to help with the rapid downselection of materials to be used within the AMBER systems. This tool created a common material performance index (γ) for all alternative and baseline materials to systematically compare the relative performance of the materials within each part of the system design.

Each performance category was assigned a weighting factor (α), relative to how important that category was to the overall performance of that part of the concept design (i.e. the fabric performance needs of the main shirt material are different from that of the torso stretch panel). Each performance test is also assigned a weighting factor (α) relative to how important that test was to describe the overall performance category for a particular concept. The digital logic method with an expert panel (comprised of TPACC faculty and staff) was used to determine the relative importance of categories and test methods.

All test data within each test is normalized on a 100-point scale with 100 being the best performing. For a given property, the normalized value is given by the scaling factor (β). Depending on the direction of desired performance of a property, the below equations are used to calculate the scaling factor.

For properties where maximum values are more desirable (i.e. Abrasion, Tensile Strength) the scaling factor equation is:

$$\beta = \frac{numerical\ value\ of\ property}{maximum\ value\ in\ the\ list} \times 100$$

For properties where minimum or low values are more desirable (i.e. Char Length, Stiffness, and Cost) the scaling factor equation is:

$$\beta = \frac{lowest\ value\ in\ the\ list}{numerical\ value\ of\ property} \times 100$$

The performance index (γ) for a particular material within each category is given by:

$$\gamma = \Sigma\alpha\beta$$

The performance indexes for each material are then sorted from high to low, providing a relative performance ranking among alternatives. This process was completed for each type of material during each testing phase and the results were used to help inform the downselection decisions. Figure 20 shows a visual depiction of the framework for the multicriteria decision tool.

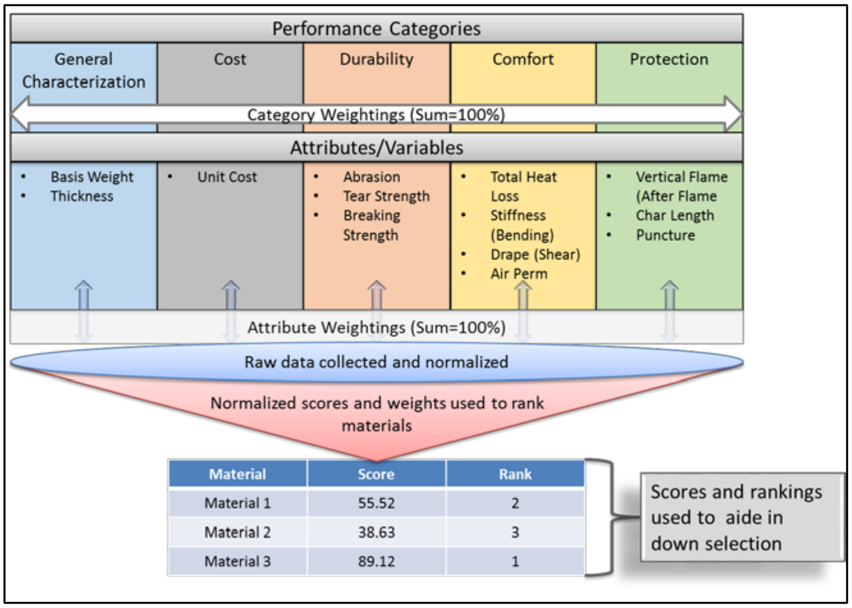


Figure 20: Multicriteria decision tool created and used for AMBER material downselection

After completion of testing and development of performance rankings, tradeoff analysis was conducted using the decision tool to help further define the rankings and to ensure that any additional constraints, practicality considerations, and stakeholder requirements were considered for each alternative material. No decisions were made based solely on the performance rankings. For example, consider the situation where a fabric ranks number one in all performance categories and in overall performance, however, the manufacturer does not produce it in the required color(s). This would be an additional tradeoff to consider during downselection and would be addressed during the tradeoff analysis step of downselection. Therefore, before any downselection was made, the tradeoff analysis was conducted to maximize success and optimize performance.

APPENDIX E: Material and System Test Method Descriptions

ASTM D3776 Basis Weight

To accurately measure the basis weight of the AMBER project fabrics, ASTM D3776 (test method for mass per unit area of fabric) was used. The weight of a fabric is measured by weighing a conditioned sample of a predetermined size on a certified scale. Using traditional US conversion methods, the final weight/unit area (oz/yd^2) is calculated from the initial weight/unit area of the sample.

ASTM D1777 Thickness

As discussed herein, the thickness of fabrics often translates directly to negative or positive influences on both objective and subjective comfort as well as durability and protection performance. ASTM D1777 is the standard test method for measuring the thickness of textile materials. Fabrics, unlike solid materials, are known to change their thickness based on given conditions, structure, and external stresses. Placing any pressure on a fabric, despite the type of fibers used, will change the thickness due to movement of the individual fibers and yarns around each other. To standardize the measurement of fabric thickness, ASTM requires a fixed pressure dependent on the material measured. The deadweight mass, the diameter of dead weight and anvil, the pressure applied, and sample conditioning are all standardized to maximize the possibility of repeatable measurements. The space between the bottom anvil and the top presser foot is the resultant measured thickness of the fabric.

ASTM D4966 Martindale Abrasion Test

Currently, there is no agreed upon (as satisfactory) standard for determining a fabric's abrasion resistance. The discrepancy is not due to any issues with the mechanism for testing; it is due to the unreliability of abrasion as a measurable characteristic, even though the general consensus is that abrasion resistance is a critical measure of a fabric's durability. Conditions such as the type of abradant used, the specific action of the abradant over the fabric, the pressure between the specimen and abradant, the tension of the sample, as well as any dimensional changes to the specimen over the course of the test. Since there are many different types of abradant surfaces, and each one is subject to variable wear over time, repeatability from one test to the next is difficult. The Martindale abrasion test is the most widely used abrasion test both in and out of the United States. The test is performed by subjecting the fabric sample to rubbing motion that starts as a straight line in one direction and gradually transitions through an oval shape until it becomes a straight line in the opposite direction. The apparatus applies constant tension and pressure on the sample while counting the number of cycles performed until the abradant makes contact with the surface below the sample or until the test is stopped. Testing thicker fabrics or highly durable fabrics with this method can be very time consuming, requiring the performance of upwards of 30,000 cycles. Because of this inconvenience, operators will often stop the test after a satisfactory number of cycles has been reached.

ASTM D1424 Elmendorf Tear Test

As tear formation occurs at the site of imperfection/damage, to test a fabric's resistance to tearing it is necessary to first start a tear and then use some method to determine how much force is necessary to propagate that tear through the fabric. A widely used method and the method employed for the testing of the AMBER fabrics is the ASTM D1424 Elmendorf Tear Test. A cut is placed in the fabric to create a standardized single-rip tear. By placing this now compromised fabric into a falling pendulum (Elmendorf) device which grips both sides of the tear and using the force of the falling pendulum mass to move each side away from each other, operators can determine the force required to propagate the tear by simply multiplying the full scale capacity (weight added to the pendulum by the operator prior to the test) by the reading from the pendulum scale.

ASTM D3787 Ball Burst Test

The structure of knits allows them to be extensible in all directions, meaning that a simple grab and pull test cannot accurately describe their strength. Therefore, knits must be tested in a way that stresses the material equally in the warp and weft directions. To solve the problem, ASTM D3787 places conditioned knit fabrics over top of a steel ball and clamps them in place. The steel ball is pressed into the material at a constant rate of elongation until failure. Similar to the tensile strength test, the average force applied (in all directions; this test does not distinguish between warp and weft) at burst is the reported value.

ASTM D5034 Tensile Strength Test (Breaking Strength)

The tensile strength test is used to determine the effective strength of a fabric. Effective strength is the numerical representation of the strength of yarns within a specific width of fabric including the additional strength imparted by nearby yarns within the weave structure. The test method used for this determination is the ASTM D5034 tensile strength test method which utilizes a tensile testing machine such as an Instron tensile tester to grab both sides of a specifically sized strip of fabric and pulls the ends apart. Ideal for woven fabrics, it is not recommended for knits due to their propensity for high stretch and extreme necking of the fabric strips. Conditioned test samples should be tested in both the warp and weft directions for a better understanding of the weave structure's effects on the fabric strength. The resultant values produced by the method are simply the average force required to break the fabrics in each direction and the overall average between warp and weft.

ASTM D3512 Pilling Test

Pills on the surface of fabrics (especially knits) are considered undesirable and unsightly. They are the small balls of fibers which have formed over time due to everyday abrasion on the material. Pills form when fibers end within yarns become no longer entangled by the yarn twist and stick out from the general mass. These fibers, through abrasion, form small balls of tangled fiber which attract other free fibers and eventually form larger and larger balls of fuzz. To better understand the tendency of a fabric to pill, ASTM D3512 places test samples within a cylindrical tumbling machine lined with a lightly abrasive material such as cork. While pills do form over time, for the sake of time, small fibers are also added into the tumbling chamber and increase the speed of pill formation by providing free floating fibers which can become entangled with the already free fiber ends on the fabric. A fabric's resistance to pilling is evaluated using an arbitrary visual rating scale. That is to say, the fabrics at the end of the test are compared against photos visually representing degrees of pilling.

ASTM D2724 Test Methods for Bonded, Fused, and Laminated Apparel Fabrics (Laminate Bond Strength)

The strength of the bond between the layers in a fabric laminate after bonding is important to its long-term durability for use within a garment system. To better understand the differences in strength between possible tri-laminate options, ASTM D2724 was used to determine the strength of the tri-laminate as bonded.

ASTM F1868 Thermal Heat Loss Test (Thermal Comfort)

Clothing, especially those designed to offer additional protection, are made of materials that hinder the flow of air, moisture, and heat away from the body. It is important to understand the thermal resistance provided by such garments to possibly prevent unnecessary heat buildup and strain. While insulation values are a good fundamental basis for this understanding, it is necessary to incorporate the effect of moisture within the system. ASTM F1868 uses a bench scale sweating hot plate to calculate the total heat loss (calculation incorporating both thermal and evaporative resistance) of a fabric or fabric composite. The sweating hot plate (20" X 20") is constructed from the combination of a test plate (10" X 10"), outer guard section (5" margin surrounding test plate), and bottom guard plate within an environmental chamber (maintained in a thermoneutral state with the hot plate). The test plate is maintained at a standard skin temperature of 33-36 degrees C through the electronic heating system. To measure the thermal resistance (Rct) provided by a fabric, it is placed on the sweating hot plate in dry conditions with a uniform wind speed across its surface. Once steady state has been achieved within the system (fabric and plate are thermally identical), the power required to maintain that steady state condition is recorded. Rct is calculated using the following equation.

$$R_{ct} = (T_s - T_a)A/H_c$$

Where:

R_{ct} = the total dry heat resistance of the fabric and air layer ((°C*m^2) /W)
A = area of the test plate (m^2)
T_s = surface temperature of the plate (Celsius)

T_a = air temperature (Celsius)
H_c = power input (W)

Once the thermal resistance (dry) is calculated, the evaporative resistance (AR_{et}) can be calculated by testing the same sample in wet (sweating) conditions. To simulate the production of moisture vapor from human skin, a vapor permeable barrier is placed over the hot plate which supplies water through strategically placed pores on its surface. Once the sample is added and reaches steady state within the system, the power input is again recorded and the evaporative resistance can be calculated from the following equation.

$$AR_{et} = [(P_s - P_a)A]/[H_E - (T_s - T_a)A/R_{ct}]$$

Where:
AR_{et} = apparent evaporative resistance of the fabric and air layer (kPa×m^2/W)
P_s = water vapor pressure at the surface of the test plate (kPa)
P_a = water vapor pressure in the air surrounding the sample (kPa)
A = area of test plate (m^2)
H_t = power input (W)
T_s = surface temperature of the plate (°C)
T_a = air temperature (°C)
R_{ct} = Total thermal resistance (dry) (°C*m^2/W)

The total heat loss (dry and sweating combined) can now be calculated by the following equation.

$$Q_t = \frac{10°C}{R_{cf} + 0.04} + \frac{3.57kPa}{AR_{ef} + 0.0035}$$

Where:
Q_t = total heat loss (W/m2)
R_{cf} = average intrinsic thermal resistance of the sample (°C*m^2/W)
(calculated by subtracting the resistance of the bare plate from R_{ct})
AR_{ef} = average intrinsic thermal resistance of the sample (kPa×m^2/W)
(Calculated by subtracting the resistance of the bare plate from AR_{et})

Figure 21: Sweating Guarded Hot Plate

KES Fabric Comfort Testing

Comfort testing of fabrics at T-PACC is performed by a system of machines and test methods called the Kawabata Evaluation System (KES). The KES uses relatively low applied forces to make objective measurements of fabric hand properties. By using these low forces, the system can measure the mechanical properties and responses that accurately correspond to the way fabrics naturally deform and behave in hand manipulation.

Two tests were performed on the AMBER project samples: bending (stiffness) and shear (drape). The bending test places a standardized fabric sample into the KES-FB2 bending tester and measures bending rigidity, the force required to bend the fabric sample approximately 150° in units of gf.cm^2/cm. The higher the value obtained through this test, the greater the stiffness/resistance to bending.

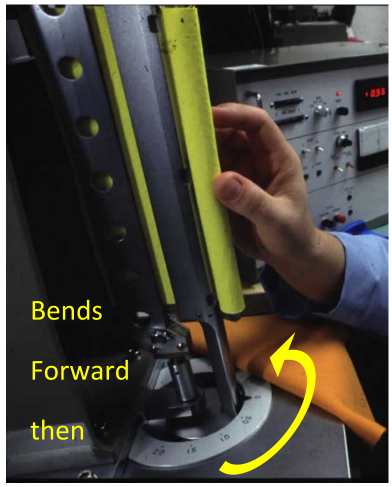


Figure 22: KES-FB2 bending tester

The shear testing is performed on the KES-FB1 tensile-shear tester. The conditioned fabric sample is loaded into the tester, a pretension of 10gf/cm is initially applied and then the tester applies opposing but parallel forces to the fabric (shearing) until a maximum angle of 8° is reached. This measurement represents the ease with which the fibers/yarns slide against each other, giving an impression of the fabric's pliability/rigidity. In this instance, the lower the values, the less the fabric resists the shearing motion.

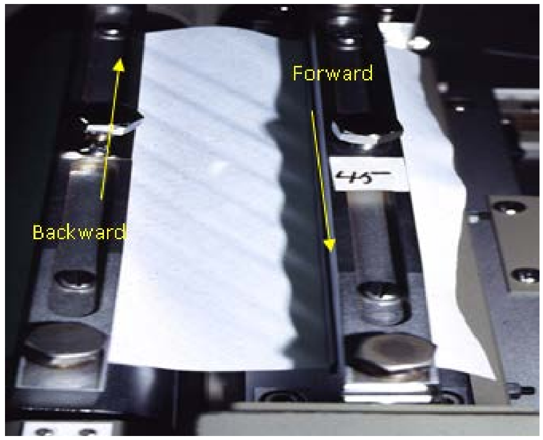


Figure 23: KES-FB1 tensile-shear tester

Vertical Wicking (NC State Internal Method)

The wicking of moisture by a fabric is regarded as an important factor in determining a material's comfort properties. Quite simply, AATCC TM 197 is a way to compare the speed of a liquid's movement within a fabric against gravity. Strips of specifically sized fabric (165x25 mm) are hung lengthwise into a pool of liquid so only the bottom 5mm is actually under the liquid's surface. Measurements are taken at specific time increments to determine the distance up the fabric the liquid traveled. Just as with most test methods, comparisons can only be made with other fabrics tested in the same manner.

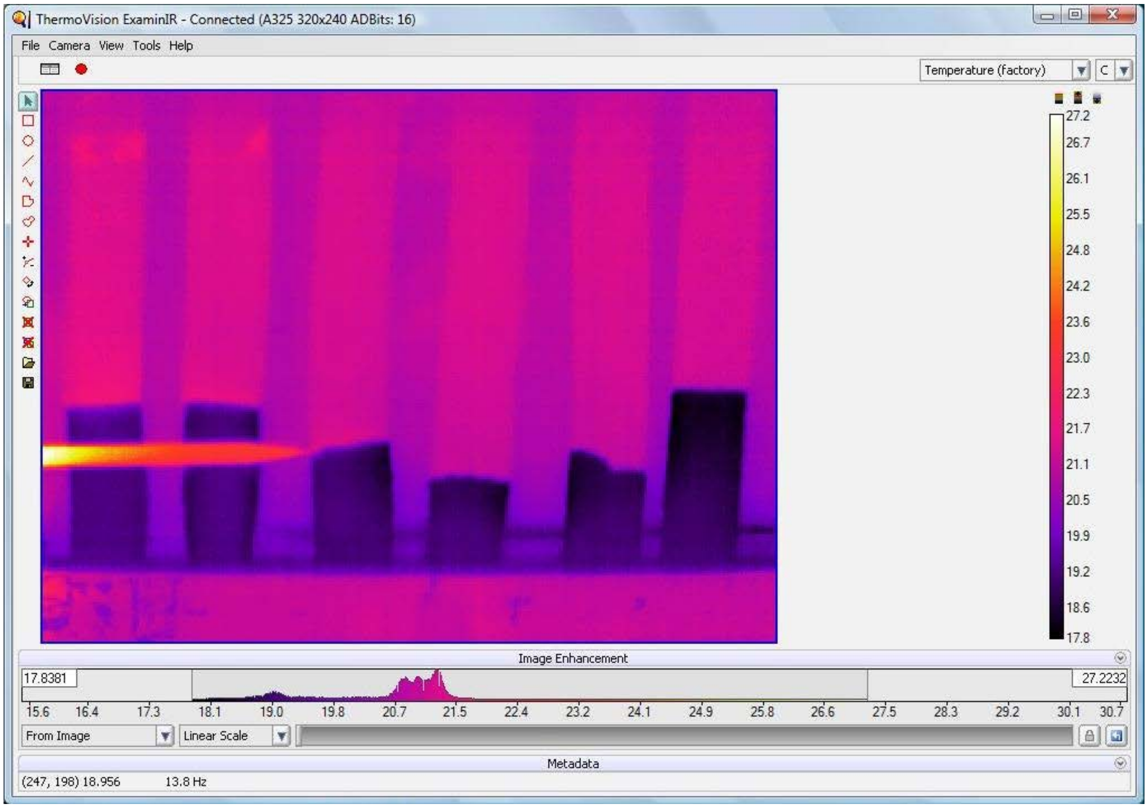


Figure 24: Thermal image of vertical wicking test

ASTM D737 Air Permeability Test

The ASTM D737 standard uses air pressure differentials between the sides of the fabric to determine the air permeability. The goal of the apparatus (Frazier Air Permeability Tester) in question is to maintain a specific air pressure (0.5 inches of water) on the machine side of the fabric by only adjusting the rate of air flowing perpendicular to the fabric surface. If a higher flow rate is necessary to maintain the pressure, the fabric has a higher air permeability, measured in cubic feet per minute (CFM). For comfort in hot/humid environments such as the AMBER garments might be used in, it is necessary to optimize the level of protection provided by the fabric and the air permeability to minimize the potential buildup of heat stress.

Figure 25: Frazier Air Permeability Tester

ASTM E96 Moisture Vapor Transmission Test

There are many test methods to determine a materials moisture vapor transmission rate (MVTR). T-PACC uses a method similar to ASTM E96 that most accurately simulates the environment in which the materials would be operating. Test samples are placed onto a small water dish (82 cm in diameter and 19 mm in depth) where the samples are precisely 9 mm above the water surface. The test dishes are placed onto a slowly rotating turntable that ensures even ambient conditions between all samples tested. The dishes of water are weighed both at the start and at the end of the test period (24 hours). This allows the true calculation of the moisture vapor transmission rate as the grams of water per area in 24 hours (g/m^2 – 24 hrs). The higher the reported value, the more moisture the sample specimen allows to pass through in a 24 hour period. This test relies on a perfectly constant and set ambient condition since the potential rate of evaporation needs to be identical between all test dishes.

Figure 26: MVTR rotating turntable

ASTM D6413 Flame Resistance Test

As discussed herein, one of the primary objectives of the AMBER garment was to make a base ensemble that complied with NFPA 1975 with the addition of the optional requirements for liquid repellency and flame resistance. The vertical flame test establishes a way to test the flame resistance response of fabrics in a standardized laboratory environment. A swatch of fabric (12 inches by 4 inches) is hung lengthwise vertically inside a draft-less static chamber over a specified ignition source. The response of the fabric to the flame is measured in three ways: char length, after-flame, afterglow, and if any melting or dripping is visible. Char length is the measured distance from the edge of the fabric exposed to the flame to the farthest location of fabric damage visible after a tearing force has been applied. After-flame is the measured time a fabric continues to burn (show visible flame) after the ignition source has been removed. Afterglow, on the other hand, is the measured time the fabric continues to luminesce (glow) after the ignition source has been removed and any residual flame has ceased. While the test does not provide an accurate representation of real-life scenarios, it is the best way to test a fabric's response to flame in a standardized manner.

ASTM F1342 Puncture Resistance Test

To ensure the fabrics used for the AMBER garment provided a desirable level of protection against puncture, ASTM F1342 was used to gather required data. The method employs three separate protocols based on the probe being used and the material to be tested. Probe A has a rounded tip of radius 0.25 mm and a shaft thickness of 2.03 mm, probe B has a full rounded tip of radius .51 mm and a shaft thickness of 1.02 mm, Probe C has a round tip of radius 0.51 mm and a shaft thickness of 2.03 mm. In each protocol, a probe is moved toward the sample surface at a constant speed and does not vary from that speed until a puncture occurs. The force required to puncture the sample is recorded as well as any elongation of the specimen that occurs before puncture. After twelve replications have been performed, the average is the reported puncture resistance.

AATCC 118 Liquid Resistance Test

To protect first responders from potential liquid hazards it was necessary to apply a fluorochemical finish to the AMBER fabrics. The treatment was designed to repel not only liquid water but also other chemicals possessing differing surface energies, such as oil. AATCC TM 118 provides a way to grade the degree to which the finish could repel such liquids. The 8 test liquids, each representing a different grade in the system, are listed below.

Table 32: Numbering of AATCC 118 test liquids with viscosities (*= extrapolated value)

#	Liquid	Dynes/cm
1	Mineral oil	31.5
2	65:35 mineral oil: hexadecane by volume	28.7*
3	Hexadecane	27.3
4	Tetradecane	26.4
5	Dodecane	24.7
6	Decane	23.5
7	Octane	21.4
8	Heptane	19.8

Starting at the lowest numbered test liquid, a drop (~5mm in diameter) is placed on the surface and observed for 30 seconds. If at the end of 30 seconds, no penetration or wetting occurs, a drop of the next highest numbered test liquid is placed on a clean area of the fabric and again observed for 30 seconds. This is continued until the fabric fails (shows obvious wetting or penetration) the test. The grade assigned to the specimen is the number of the highest numbered test liquid at which the fabric did not fail. This method is beneficial in determining the wash fastness of a fluorocarbon finish or simply assessing the initial level of repellency.

ISO 6530 Gutter Test

To ensure that the fabrics and composites being created for the first responder's base ensemble could withstand limited exposure to hazardous liquid chemicals, the ISO 6530 test method was used. Known as the gutter test, the method measures the liquid penetration and repellency of given fabrics. The gutter test places the fabric within a 45-degree inclined gutter lined with an absorbent fabric and then 10 milliliters (ml) of the chemical is released within 10 seconds at the top of the test fabric. The weights of the fabric, absorbent paper, and collection beaker are weighed before and after the test. Using those values, the following indexes can be calculated:

Absorption index (I_a) = percentage of 10 ml liquid absorbed into the fabric
Penetration index (I_p) = percentage of 10 ml liquid absorbed by the absorbent paper backing
Repellency index (I_r) = percentage of 10 ml liquid collected in beaker at end of test

The liquids used to test the AMBER fabrics and composites in the EN 6530 gutter test are as follows (provided by NFPA 1977)

1- Deionized water
2- Blood simulant
3- Gasoline simulant
4- FR Hydraulic fluid
5- 65% Calcium Hypochlorite
6- Aqueous foam forming solution
7- Sulfuric acid

Ball Drop Impact Test (Ansell Method)

A steel ball of 0.54 kg mass is remotely dropped from 0.5 m height directly on top of the material being measured. Material lays directly on top of a sensor that measures the force in Newton's. Four replicates were completed for each sample. The material thickness and the average of the peak force for the four replicates are reported for each sample type. Percent Force Attenuation was calculated using the following equation.

$$Force\ attenuated = (1 - \frac{Test\ Sample\ average\ force}{Pant\ fabric\ average\ force}) * 100$$

Force attenuated represents the percentage of force redirected by the test sample upon impact. The pant fabric sample is assumed to have 0% attenuated, representing an impact with no protection.

ASTM F2731 Standard Test Method for Measuring the Transmitted and Stored Energy of Firefighter Protective Clothing Systems

This test method provides procedures for measuring the combination of transmitted and stored energy that occurs in firefighter protective clothing material systems as the result of exposure to prolonged, relatively low levels of radiant heat. The method applies a predetermined compressive load to a preheated specimen to simulate conductive heat transfer.

APPENDIX F: Down-selection Results by Phase

Each successive Phase included a set of materials tests, a property weighting exercise, and the analysis and downselection decision.

Phase I

The main goal of the initial Phase of testing was to downselect to the 2-3 best fabrics for Type 1, 1-2 fabrics for Type 2 fabrics, and the 2-3 best membranes for Type 3 materials.

Type 1 fabric down-selection

For Phase 1 Type 1 fabrics, the performance weightings given to each test and each performance category were:

Table 33: Fabric performance categories and assigned weights for Type 1 woven fabrics

Category	Type 1
General Characterization	7%
Cost	18%
Durability	21%
Protection	25%
Comfort	29%

Table 34: Weight percentages of each performance type for AMBER Type 1 woven fabrics

Performance Type	**Type 1**
Basis Weight	50.00%
Thickness	50.00%
Unit Cost	100%
Abrasion	28.57%
Tear	42.86%
Breaking	28.57%
Thermal Comfort	17.65%
Stiffness	29.41%
Drape	29.41%
Air Permeability	23.53%
Vertical Flame	37.50%
Vertical Flame	37.50%
Puncture	25.00%

Summary data for Phase I, Type 1 fabric by performance category are shown below in Table 35 - Table 37.

Table 35: Type 1 woven fabric results for comfort related tests

Fabric	Weave	THL (W/m^2)	Stiffness ($gf*cm^2/cm$)	Drape (gf/cm*degree)	Air Permeability ($ft^3/min/ft^2$)	Wicking (inches per 5 min)
PBI Twill	Twill	775.73	0.101	0.617	101	2.72
PBI Ripstop	Ripstop	672.31	0.328	2.515	72.8	0.35
Milliken ResQ 5.6	Twill	611.07	0.18	1.519	12.1	0.43
Milliken ResQ 5.9	Twill	830.78	0.267	0.629	80.7	9.33
Milliken CXP	Plain	729.41	0.093	0.675	61.1	12.55
Tencate 580A	Twill	754.5	0.091	0.583	82.8	8.15
Tencate 700	Twill	756.02	0.189	1.06	38.9	10.27
Tencate 700A	Twill	741.83	0.14	0.886	46.7	7.25
Tencate 850A	Twill	684.97	0.165	1.005	41.7	7.67

Table 36: Type 1 woven fabric results for durability related tests

Fabric	Weave	Abrasion (cycles to a hole)	Average Tear Strength (lbf)	Average Breaking Strength (lbf)
PBI Twill	Twill	20667	14.20	149.95
PBI Ripstop	Ripstop	21333	14.20	169.30
Milliken ResQ 5.6	Twill	36001	12.50	146.50
Milliken ResQ 5.9	Twill	36001	14.15	145.50
Milliken CXP	Plain	36001	10.80	196.00
Tencate 580A	Twill	14333	10.50	92.50
Tencate 700	Twill	22333	11.00	110.00
Tencate 700A	Twill	25333	9.00	110.00
Tencate 850A	Twill	18000	11.00	117.50

Table 37: Type 1 woven fabric results for protection-related tests

Fabric	Weave	After flame (seconds)	Char length (mm)	ASTM puncture (lbf)
PBI Twill	Twill	2.2	3	3.33
PBI Ripstop	Ripstop	2.1	10	3.03
Milliken ResQ 5.6	Twill	1.0	123	2.15
Milliken ResQ 5.9	Twill	0.0	97	1.57
Milliken CXP	Plain	0.0	69	4.60
Tencate 580A	Twill	2.1	57	2.06

Fabric	Weave	After flame (seconds)	Char length (mm)	ASTM puncture (lbf)
Tencate 700	Twill	3.0	75	3.42
Tencate 700A	Twill	2.5	60	3.13
Tencate 850A	Twill	1.2	57	2.64

Based on the analysis conducted during the Phase I downselection process, the following Type 1 materials were selected to move to Phase 2.

Table 38: Phase I downselected Type 1 woven fabrics

DOWNSELECTED TYPE 1 FABRICS			
FABRIC	**FIBER CONTENT**	**BASIS WEIGHT**	**TRADEOFFS**
Milliken CXP Plain	Nomex	6.0 oz/yd^2	Highest rated, high durability, unsure of color availability, cost is high
PBI Twill	50% Twaron, 30% FR Viscose, 20% PBI	4.8 oz/yd^2	Cost is very high (highest among alternatives)
Milliken ResQ 5.9	37% Aramid, 33% Synthetic, 30% Cellulosic	5.6 oz/yd^2	High durability, high cost
Tencate Tecasafe 580A	Modacrylic, Cellulose, Aramid	6.2 oz/yd^2	High comfort, low cost, mediocre durability

Type 2 Fabric Downselection

For Phase 1 Type 2 fabrics, the performance weightings given to each test and each performance category were:

Table 39: Weight percentages of each performance category for AMBER Type 2 knit fabrics

Category	Weight Value
General	7%
Cost	18%
Durability	25%
Comfort	29%
Protection	21%

Table 40: Weight percentages of each performance type for AMBER Type 2 knit fabrics

Performance Type	Weight Value
Basis Weight	50%
Thickness	50%
Cost	100%
Burst	33%
Pilling	66.66%
THL	22%
Wicking	33%
Air Permeability	44.44%
Afterflame	50%
Charlength	50%

Table 41: Type 2 knit test results for comfort related tests

Fabric	Construction	THL (W/m^2)	Stiffness (gf*cm2/ cm)	Drape (gf/cm *degree)	Wicking (in. in 5 min)	Air permeability ($ft^3/min/ft^2$)
Polartec 2014	Jersey	686.1	0.018	0.577	9.98	310
Polartec 2012	Mesh	630.9	0.010	0.576	9.08	553
Massif Battleskin	Jersey	769.2	0.088	1.777	4.90	363
Massif Helium	Jersey	591.2	0.024	0.602	6.80	120
Massif Blaze	Jersey	580.9	0.031	1.319	4.65	88.3
Massif Breeze	Pointelle Mesh	637.5	0.056	0.627	6.15	243

Table 42: Type 2 knit test results for durability related tests

Fabric	Construction	Burst (lbf)	Pilling (visual rating)
Polartec 2014	Jersey	57.9	3
Polartec 2012	Mesh	53.5	3
Massif Battleskin	Jersey	126.7	3
Massif Helium	Jersey	40.5	4
Massif Blaze	Jersey	72.2	5
Massif Breeze	Pointelle Mesh	37.5	5

Table 43: Type 2 knit test results for protection related tests

Fabric	Construction	After flame (seconds)	Char length (mm)
Polartec 2014	Jersey	1.7	98
Polartec 2012	Mesh	1.9	107
Massif Battleskin	Jersey	2.6	101
Massif Helium	Jersey	1.4	82
Massif Blaze	Jersey	0.1	88
Massif Breeze	Pointelle Mesh	0.1	93

Based on the analysis conducted during the Phase I down-selection process, the following Type 2 materials were selected to move to Phase 2.

Table 44: Phase I downselected Type 2 knit fabrics

DOWNSELECTED TYPE 2 KNIT FABRICS			
FABRIC	**FIBER CONTENT**	**BASIS WEIGHT**	**TRADEOFFS**
Massif Breeze	87% Cotton, 7% Poly, 6% Spandex	5.5 osy	Overall good performer, but is mesh/
Polartec 2012	72% Modacrylic, 28% Rayon	5.2 osy	Highest Comfort
Massif Blaze	93% Cotton, 7% Spandex	6.9 osy	High Protection and Durability

Type 3 Membrane Down-selection

Prior to selecting a tri-laminate combination, several membranes were sourced and tested for moisture vapor transmission rate (MVTR) and liquid resistance via test method AATCC 118. Those results are shown below.

Table 45: Membrane only test results

Membrane	Polymer	MVTR ($g/m^2/24hrs$)	Liquid Resistance (rating)
Porelle® P540FR	polyurethane	506	4
Agrotec TX1540	polyurethane	702	1
Agrotec TX4100	polyurethane	725	1
°eVent®	e-ptfe	721	1
Porelle® P345	polyurethane	418	4
Porelle® P55	polyurethane	597	5

Based on the analysis conducted during the Phase I down-selection process and the membrane only results shown in Table 45, the following Laminate combinations were planned for the lamination trial (Table 46).

Table 46: Tri-laminate configurations for initial testing

Laminate ID	Next to Skin	Membrane	Outer Layer	Weight (oz/yd^2)	Thickness (mm)
L1	Polartec 2012	eVent	PBI Twill	11.3	0.97
L2	Polartec 2012	eVent	Tencate 580A	13.0	1.11
L3	Polartec 2012	eVent	Milliken CXP	12.4	1.12
L4	Polartec 2012	TX4100	PBI Twill	11.2	0.96
L5	Polartec 2012	TX4100	Tencate 580A	12.2	1.05
L6	Polartec 2012	TX4100	Milliken CXP	12.2	1.12
L7	Polartec 2012	P540FR	PBI Twill	12.0	0.97
L8	Polartec 2012	P540FR	Tencate 580A	13.4	1.12
L9	Polartec 2012	P540FR	Milliken CXP	13.3	1.20
L10	Polartec 2014	eVent	PBI Twill	10.9	0.81
L11	Polartec 2014	eVent	Tencate 580A	12.6	0.91
L12	Polartec 2014	eVent	Milliken CXP	11.8	0.91
L13	Polartec 2014	TX4100	PBI Twill	10.5	0.78
L14	Polartec 2014	TX4100	Tencate 580A	12.0	0.89
L15	Polartec 2014	TX4100	Milliken CXP	12.2	0.95
L16	Polartec 2014	P540FR	PBI Twill	12.3	0.83
L17	Polartec 2014	P540FR	Tencate 580A	13.3	0.91
L18	Polartec 2014	P540FR	Milliken CXP	13.2	0.97
L19	Massif Battleshield (trilaminate)			7.3	0.65

Phase 2

After the materials were down-selected in the first Phase, the next Phase of testing and down-selection was conducted to ensure that the available materials for Type 1 and Type 2 were tested to see if they could pass the required thermal tests in order to be certified to the NFPA 1975 standard. Type 3 membranes were laminated to the most acceptable options from Type 1 and 2 materials, creating 18 different tri-laminate options to test for Phase 2.

Type 1 and 2 Fabric Down-selection for Phase 2

Both Type 1 and Type 2 materials were tested to a couple of the critical tests needed to pass NFPA 1975: the Thermal Stability and Thermal Shrinkage tests. Since NFPA certification was a requirement for this project, any fabrics failing these tests needed to be eliminated.

Table 47: Phase 2 NFPA 1975 Thermal Shrinkage and Thermal Stability Results Summary

Materials	Thermal Shrinkage Warp	Thermal Shrinkage Fill	Thermal Stability (blocking)	Thermal Stability (sticking)
Tencate 580A	-3.1	-4.7	1	N
PBI Twill	-2.8	-2.3	1	N
Milliken CXP	-1.1	-1.1	2	Y
Milliken ResQ 5.9	-6	-1.9	3	Y
Polartec 2012	-20	-20	3	N
Massif Blaze	3.3	2.1	1	N
Massif Breeze	>10	-6.5	2	N

Based on this testing, the Milliken CXP, Milliken ResQ 5.9 and the Polartech 2012 were eliminated, due to failures during the NFPA 1975 required tests of thermal shrinkage and thermal stability.

Table 48: Phase 2 Type 1 downselected fabrics

DOWNSELECTED TYPE 1 FABRICS			
FABRIC	**FIBER CONTENT**	**BASIS WEIGHT**	**TRADEOFFS**
PBI 4.5 Twill	50% Twaron, 30% FR Viscose, 20% PBI	4.8 osy	Cost is very high (highest among alternatives)
Tencate Tecasafe 580A	Modacrylic, Cellulose, Aramid	6.2 osy	High comfort, low cost, mediocre durability

Table 49: Phase 2 Type 2 downselected fabrics

DOWNSELECTED TYPE 2 FABRICS			
FABRIC	**FIBER CONTENT**	**BASIS WEIGHT**	**TRADEOFFS**
Massif Breeze	87% Cotton, 7% Poly, 6% Spandex	5.5 osy	Overall good performer
Massif Blaze	93% Cotton, 7% Spandex	6.9 osy	High Protection and Durability

Type 3 trilaminate Down-selection

For the tri-laminate materials, the overall objective was to eliminate potential poor performing options based on a slightly higher weighting for the protection measures versus the comfort and durability measures. The weightings and test data are shown below.

Table 50: Weight percentages of each performance category for AMBER laminates

Category	Weight Value
General	14%
Cost	17%
Durability	21%
Comfort	21%
Protection	28%

Table 51: Weight percentages of each performance type for AMBER laminates

Performance Type	Weight Value
Basis Weight	50%
Thickness	50%
Cost	100%
Bond Strength (front)	50%
Bond Strength (Back)	50%
Stiffness	50%
Drape	50%
Afterflame	50%
Charlength	50%

Table 52: Phase 2 Tri-laminate initial testing results

Laminate ID	Stiffness (gf*cm2/cm)	Drape (gf/cm*degree)	Avg. After flame (seconds)	Avg. Char length (mm)	Laminate Bond Strength-back (lbf/in)
L1	0.290	5.08	3.6	12	0.69
L2	0.366	5.05	1.0	38	0.44
L3	0.423	4.55	3.7	32	0.47
L4	0.303	5.79	3.4	10	2.06
L5	0.355	5.84	3.0	58	2.25
L6	0.484	5.64	2.6	38	1.52
L7	0.518	8.77	2.7	3	0.77
L8	0.527	9.60	4.0	59	1.13

Laminate ID	Stiffness (gf*cm2/cm)	Drape (gf/cm*degree)	Avg. After flame (seconds)	Avg. Char length (mm)	Laminate Bond Strength-back (lbf/in)
L9	1.000	9.78	4.3	41	0.88
L10	0.681	5.68	1.3	8	0.55
L11	0.770	5.43	4.0	44	0.49
L12	0.999	5.99	2.3	33	1.40
L13	0.645	5.66	2.7	28	1.40
L14	0.717	5.67	5.4	63	2.25
L15	0.951	6.08	0.5	35	2.36
L16	1.000	8.70	3.1	5	2.45
L17	0.449	9.48	4.5	61	2.15
L18	1.001	9.69	0.1	53	2.04
L19	0.419	5.08	2.0	101	1.40

Due to the poor performance of the CXP and the 2012 fabrics in the heat and thermal shrinkage tests, and that 2014 was already eliminated (it also didn't pass the heat and thermal shrinkage tests), all potential tri-laminate options tested in phase 2 were no longer viable options. Therefore, the continued development of a tri-laminate occurred, that included the materials that had already been selected for continued testing. However, the TX4100 membrane did come out as the best membrane within the overall laminated system, consistently performing high in each of the key categories. Once the membrane was selected, a new tri-laminate option was created with the Tencate 700A, TX4100 and Massif Blaze, taking advantage of reducing the overall garment supply chain and taking into consideration the cost of the overall tri-laminate conversion. Phase 3 tested the tri-laminate repellency characteristics to confirm the overall configuration was acceptable.

Phase 3

Phase 3 downselection was the final phase of material selection for the materials to be used in the main design elements of the MBE Level I and Level II design concepts. The goal of the third phase of downselection was to determine the final set of materials to be used for each Type of fabric.

Type 1

Since one of the key performance measures for Type 1 fabric in both MBE concepts was the durable liquid splash protection performance, the third phase focused on adding antimicrobial and omniphobic chemistry to the fabric and then testing the durable liquid repellency for those materials in order to do a final material downselection.

Type 2

Based on the performance of the remaining Type 2 materials (Massif Breeze and Massif Blaze), both materials found a specific place in the system design. Based on their comfort and stretch properties, the Breeze was selected to be used for the MBE Level 1 in the venting areas and the Blaze was selected to be used in both MBE Level 1 and Level 2 designs in areas where moisture wicking, antimicrobial performance and added stretch for comfort were desired (back of knees, crotch gusset, and back trouser yoke). However, even though it had passed in the previous testing, the Massif Breeze material did not pass the thermal stability testing during NFPA certification. Therefore, the decision was made to replace the Breeze material with the Blaze fabric for the final AMBER prototype system.

Type 3

Since the CXP, 2012 and 2014 were eliminated for failing to meet the NFPA 1975 requirements, we eliminated any tri-laminate option that included CXP, 2012 or 2014. This required that we eliminate all current options since they all included a base fabric of either 2012 or 2014. Since all of our options were eliminated, we used the highest rated membrane and laminated it to the Type 1 and Type 2 materials to create the final laminate to be used for the AMBER prototypes. This combination of the tri-laminate was tested during Phase 3.

APPENDIX G: Material Finish Technology

An important part of the overall AMBER material performance is the Durable Omniphobic Repellency (DOR) and the antimicrobial (AM) performance. Each of these performance attributes was made possible through the use of newly available chemistry, direct communication with relevant chemical suppliers, and through use of NC State's wet processing pilot plant facilities. During the material selection process, none of the off the shelf materials selected had sufficient repellency features to meet the AMBER requirements and had to be developed. Therefore, we were able to use our knowledge of the finishing technology available and our in-house capabilities to build in the desired functionality during the material selection process.

During the second phase of material selection, we took the three potential Type 1 materials selected and conducted lab scale finishing trials with formula combinations of the DOR and antimicrobial.

Figure 27: Lab scale treatment of AMBER material options during development

After completion of the finishing trials on the selected Type 1 fabrics (woven), each was tested for repellency to the AATCC 118 chemical list at the pristine condition (i.e. zero laundering). To ensure durability, each test fabric was also laundered up to 15 times with additional AATCC 118 testing at each five wash interval. Testing was then compared for the best repellent and durable combination of treatment, which was then factored into the final material selection decisions.

Further to the development of the material treatment capabilities, NC State internally developed and scaled up the finishing at the NC State pilot plant for materials used in for the 150 AMBER prototypes. A full-scale pad and tenter frame were used to treat the AMBER materials. This scale up production process for the DOR and AM materials will be transitioned to the appropriate fabric supplier as PTF moves forward with commercialization.

Figure 28: Full-scale fabric wet processing at NC State's pilot plant for the final AMBER materials

APPENDIX H: Heated Sweating Manikin Test Conditions

Table 53: Heated Sweating Manikin Thermal Resistance Test Conditions

Test Conditions – Thermal Resistance	**Standing**	**Walking**
Air Temperature (°C)	20	20
RH (%)	50	50
Air Speed (m/s)	0.4	1.0
Skin Temperature (°C)	35	35

Table 54: Heated Sweating Manikin Evaporative Resistance Test Conditions

Test Conditions- Evaporative Resistance	**Standing**	**Walking**
Air Temperature (°C)	35	35
RH (%)	40	40
Air Speed (m/s)	0.4	1.0
Skin Temperature (°C)	35	35

APPENDIX I: Human Subject Evaluation documentation

This section provides supplemental documentation including Institutional Review Board (IRB) approval for the human subject wear trial that was conducted with the AMBER system. A total of 20 participants were recruited for evaluation and trials were conducted over a two week time period.

IRB Approval For Protocol 6507

NORTH CAROLINA STATE UNIVERSITY
INSTITUTIONAL REVIEW BOARD FOR THE USE OF HUMAN SUBJECTS IN RESEARCH
SUBMISSION FOR NEW STUDIES

Protocol Number 6507

Project Title
Advanced Multi-hazard Base ensemble for Emergency Responders (AMBER) System Level Comfort Evaluation

IRB File Number:

Original Approval Date:
12/17/2015

Approval Period
12/17/2015 - 12/17/2016

Source of funding (if externally funded, enter PINS or RADAR number of funding proposal via 'Add New Sponsored Project Record' button below):
External-Department of Homeland Security

NCSU Faculty point of contact for this protocol:NB: only this person has authority to submit the protocol
Mathews, Marc C: Textile Protection & Comfort Center

Does any investigator associated with this project have a significant financial interest in, or other conflict of interest involving, the sponsor of this project? (Answer No if this project is not sponsored)
No

Is this conflict managed with a written management plan, and is the management plan being properly followed?
No

Preliminary Review Determination

Category:
Expedited 4, 7

In lay language, provide a brief synopsis of the study (limit text to 1500 characters)
This study will be to compare the comfort and functionality performance for first responder daily wear uniforms. This study will include one newly developed uniform and up to three commercially available uniforms.

Briefly describe in lay language the purpose of the proposed research and why it is important.
The Department of Homeland Security (DHS) has identified a need for a multi-hazard protective daily wear uniform. NC State's Textile Protection and Comfort Center (TPACC) has developed a new garment system to meet the needs identified by DHS. This evaluation is to provide a comparison between the newly developed system and commercially available systems.

My research qualifies for Exemption. Exempt research is minimal risk and must fit into the categories b.1 - b.6 found here: http://www.hhs.gov/ohrp/humansubjects/guidance/45cfr46.html
0

Is this research being conducted by a student?
No

Is this research for a thesis?
No

Is this research for a dissertatiion?
No

Is this independent research?
No

Is this research for a course?
No

Do you currently intend to use the data for any purpose beyond the fulfillment of the class assignment?
No

Please explain

The following sections include the fit assessment tables and wear trial questionnaires used during the wear trial protocol.

Fit Determination Tables

Perceived comfort scale (ISO 10551, 2001)

Question asked by the researcher: ***"How do you perceive your whole body comfort at this moment****?"*

Rating	
0	Comfortable
1	Slightly uncomfortable
2	Uncomfortable
3	Very uncomfortable
4	Extremely uncomfortable

Question asked by the researcher: **"How do you perceive the fit of this garment?"**

Rating	
0	Exceptional Fit
1	Good Fit
2	Acceptable Fit
3	Poor Fit
4	Extremely Poor Fit

Donning and Initial Impression Evaluation Form

DATE __________ Evaluator ID __________ Ensemble ID ________

Select the one best response for each item:

1. Overall Comfort

(7) very comfortable
(6) comfortable
(5) slightly comfortable
(4) neither comfortable nor uncomfortable
(3) slightly uncomfortable
(2) uncomfortable
(1) very uncomfortable

2. Breathability

(7) very cool / breathable
(6) cool / breathable
(5) slightly cool / breathable
(4) neutral
(3) slightly warm / nonbreathable
(2) warm / nonbreathable
(1) very warm / nonbreathable

3. Softness

(7) very soft
(6) soft
(5) slightly soft
(4) neither soft nor harsh
(3) slightly harsh
(2) harsh
(1) very harsh

4. Ease of Donning

(7) very easy
(6) easy
(5) slightly easy
(4) neither easy nor difficult
(3) slightly difficult
(2) difficult
(1) very difficult

5. Aesthetic

(7) very attractive
(6) attractive
(5) slightly attractive
(4) neither attractive nor unattractive
(3) slightly unattractive
(2) unattractive
(1) very unattractive

6. **Appearance**

(7) very professional
(6) professional
(5) slightly professional
(4) neither professional nor unprofessional
(3) slightly unprofessional
(2) unprofessional
(1) very unprofessional

7. **Temperature Sensation**

(7) very cool
(6) cool
(5) slightly cool
(4) neither cool nor warm
(3) slightly warm
(2) warm
(1) very warm

Rate the degree to which you sense each property:

Property	Totally	Mostly	Mildly	Slightly	No sensation
8. Tight	(1)	(2)	(3)	(4)	(5)
9. Heavy	(1)	(2)	(3)	(4)	(5)
10. Stiff	(1)	(2)	(3)	(4)	(5)
11. Rough	(1)	(2)	(3)	(4)	(5)
12. No stretch	(1)	(2)	(3)	(4)	(5)
13. Inflexible	(1)	(2)	(3)	(4)	(5)

Was it easy to assess the fabric in this activity? Yes No (circle response)

Add voluntary comments:

Wear Test Response Questionnaire

Evaluator ID __________ Ensemble ID ________ DATE _______________

Period 4: Following warm up and sitting at rest for 10 minutes

Select the one best response for each item as related to the **SHIRT** component**.**

1. Overall Comfort

(7) very comfortable

(6) comfortable

(5) slightly comfortable

(4) neither comfortable nor uncomfortable

(3) slightly uncomfortable

(2) uncomfortable

(1) very uncomfortable

2. Breathability

(7) very cool / breathable

(6) cool / breathable

(5) slightly cool / breathable

(4) neutral

(3) slightly warm / nonbreathable

(2) warm / nonbreathable

(1) very warm / nonbreathable

3. Moisture Sensation in Shirt

(7) totally dry

(6) slight dampness sensation in shirt

(5) upper back area beginning to sweat

(4) upper back area feels mostly wet

(3) some sweat dripping down torso

(2) heavy sweat dripping down torso

(1) lower torso feels wet all over / profusely sweating

4. Moisture Sensation by Location (circle appropriate level)

Collar:	None	Slight	Moderate	Heavy
Underarms:	None	Slight	Moderate	Heavy
Back:	None	Slight	Moderate	Heavy
Front:	None	Slight	Moderate	Heavy

5. Softness

(7) very soft

(6) soft

(5) slightly soft

(4) neither soft nor harsh

(3) slightly harsh

(2) harsh

(1) very harsh

Rate the degree to which you sense each quality:

Property	**Totally**	**Mostly**	**Mildly**	**Slightly**	**No sensation**
6. Tight	(1)	(2)	(3)	(4)	(5)
7. Heavy	(1)	(2)	(3)	(4)	(5)
8. Stiff	(1)	(2)	(3)	(4)	(5)
9. Sticky	(1)	(2)	(3)	(4)	(5)
10. Nonabsorbent	(1)	(2)	(3)	(4)	(5)
11. Nonbreathable (hot)	(1)	(2)	(3)	(4)	(5)
12. Damp	(1)	(2)	(3)	(4)	(5)
13. Clingy	(1)	(2)	(3)	(4)	(5)
14. Rough	(1)	(2)	(3)	(4)	(5)
15. No stretch	(1)	(2)	(3)	(4)	(5)

Add voluntary comments:

Evaluator ID ___________ Ensemble ID _________ DATE ________________

Period 4: Following warm up and sitting at rest for 10 minutes

Select the one best response for each item as related to the **PANTS** component.

1. Overall Comfort

(7) very comfortable
(6) comfortable
(5) slightly comfortable
(4) neither comfortable nor uncomfortable
(3) slightly uncomfortable
(2) uncomfortable
(1) very uncomfortable

2. Breathability

(7) very cool / breathable
(6) cool / breathable
(5) slightly cool / breathable
(4) neutral
(3) slightly warm / nonbreathable
(2) warm / nonbreathable
(1) very warm / nonbreathable

3. Moisture Sensation in Pants

(7) totally dry

(6) slight dampness sensation in pants

(5) upper thigh area beginning to sweat

(4) upper thigh area feels mostly wet

(3) some sweat dripping down legs

(2) heavy sweat dripping down legs

(1) lower torso feels wet all over / profusely sweating

4. Moisture Sensation by Location (circle appropriate level)

Waist:	None	Slight	Moderate	Heavy
Seat:	None	Slight	Moderate	Heavy
Legs:	None	Slight	Moderate	Heavy

5. Softness

(7) very soft

(6) soft

(5) slightly soft

(4) neither soft nor harsh

(3) slightly harsh

(2) harsh

(1) very harsh

Rate the degree to which you sense each quality:

Property	Totally	Mostly	Mildly	Slightly	No sensation
6. Tight	(1)	(2)	(3)	(4)	(5)
7. Heavy	(1)	(2)	(3)	(4)	(5)
8. Stiff	(1)	(2)	(3)	(4)	(5)
9. Sticky	(1)	(2)	(3)	(4)	(5)
10. Nonabsorbent	(1)	(2)	(3)	(4)	(5)
11. Nonbreathable (hot)	(1)	(2)	(3)	(4)	(5)
12. Damp	(1)	(2)	(3)	(4)	(5)
13. Clingy	(1)	(2)	(3)	(4)	(5)
14. Rough	(1)	(2)	(3)	(4)	(5)
15. No stretch	(1)	(2)	(3)	(4)	(5)

Add voluntary comments:

Evaluator ID ___________ Ensemble ID _________ DATE ________________

Period 6: Following leg and knee tasks and sitting at rest for 10 minutes.

Select the one best response for each item as related to the **PANTS** component.

1. Overall Comfort in Pants

(7) very comfortable
(6) comfortable
(5) slightly comfortable
(4) neither comfortable nor uncomfortable
(3) slightly uncomfortable
(2) uncomfortable
(1) very uncomfortable

2. Breathability in Pants

(7) very cool / breathable
(6) cool / breathable
(5) slightly cool / breathable
(4) neutral
(3) slightly warm / nonbreathable
(2) warm / nonbreathable
(1) very warm / nonbreathable

3. Moisture Sensation in Pants

(7) totally dry
(6) slight dampness sensation in pants
(5) upper thigh area beginning to sweat
(4) upper thigh area feels mostly wet
(3) some sweat dripping down legs
(2) heavy sweat dripping down legs
(1) lower torso feels wet all over / profusely sweating

4. Moisture Sensation by Location (circle appropriate level)

Waist:	None	Slight	Moderate	Heavy
Seat:	None	Slight	Moderate	Heavy
Backside:	None	Slight	Moderate	Heavy
Knees:	None	Slight	Moderate	Heavy

5. Comfort Level by Location (circle appropriate level)

Waist:	None	Slight	Moderate	Very
Seat:	None	Slight	Moderate	Very
Backside:	None	Slight	Moderate	Very
Knees:	None	Slight	Moderate	Very

Rate the degree to which you sense each quality:

Property	Totally	Mostly	Mildly	Slightly	No sensation
6. Tight	(1)	(2)	(3)	(4)	(5)
7. Heavy	(1)	(2)	(3)	(4)	(5)
8. Stiff	(1)	(2)	(3)	(4)	(5)
9. Sticky	(1)	(2)	(3)	(4)	(5)
10. Nonabsorbent	(1)	(2)	(3)	(4)	(5)
11. Nonbreathable (hot)	(1)	(2)	(3)	(4)	(5)
12. Damp	(1)	(2)	(3)	(4)	(5)
13. Clingy	(1)	(2)	(3)	(4)	(5)
14. Rough	(1)	(2)	(3)	(4)	(5)
15. Nonstretchy	(1)	(2)	(3)	(4)	(5)

Add voluntary comments:

Evaluator ID ___________ Ensemble ID _________ DATE ________________

Period 8: Following upper stretch movements and sitting at rest for 10 minutes

Select the one best response for each item as related to the **SHIRT** component.

1. **Overall Comfort in Shirt**

(7) very comfortable
(6) comfortable
(5) slightly comfortable
(4) neither comfortable nor uncomfortable
(3) slightly uncomfortable
(2) uncomfortable
(1) very uncomfortable

2. **Breathability in Shirt**

(7) very cool / breathable
(6) cool / breathable
(5) slightly cool / breathable
(4) neutral
(3) slightly warm / nonbreathable
(2) warm / nonbreathable
(1) very warm / nonbreathable

3. Moisture Sensation in Shirt

(7) totally dry

(6) slight dampness sensation in shirt

(5) upper back area beginning to sweat

(4) upper back area feels mostly wet

(3) some sweat dripping down torso

(2) heavy sweat dripping down torso

(1) lower torso feels wet all over / profusely sweating

4. Moisture Sensation by Location (circle appropriate level)

Collar:	None	Slight	Moderate	Very
Underarms:	None	Slight	Moderate	Very
Back:	None	Slight	Moderate	Very
Front:	None	Slight	Moderate	Very

5. Comfort Level by Location (circle appropriate level)

Collar:	None	Slight	Moderate	Very
Underarms:	None	Slight	Moderate	Very
Back:	None	Slight	Moderate	Very
Front:	None	Slight	Moderate	Very

Rate the degree to which you sense each quality:

Property	Totally	Mostly	Mildly	Slightly	No sensation
6. Tight	(1)	(2)	(3)	(4)	(5)
7. Heavy	(1)	(2)	(3)	(4)	(5)
8. Stiff	(1)	(2)	(3)	(4)	(5)
9. Sticky	(1)	(2)	(3)	(4)	(5)
10. Nonabsorbent	(1)	(2)	(3)	(4)	(5)
11. Nonbreathable (hot)	(1)	(2)	(3)	(4)	(5)
12. Damp	(1)	(2)	(3)	(4)	(5)
13. Clingy	(1)	(2)	(3)	(4)	(5)

Property	Totally	Mostly	Mildly	Slightly	No sensation
14. Rough	(1)	(2)	(3)	(4)	(5)
15. Nonstretchy	(1)	(2)	(3)	(4)	(5)

Add voluntary comments:

Evaluator ID ___________ Ensemble ID _________ DATE ________________

Period 10: Following full body engagement tasks and sitting at rest for 10 minutes

Select the one best response for each item as related to the whole **Ensemble**.

1. Overall Comfort

(7) very comfortable
(6) comfortable
(5) slightly comfortable
(4) neither comfortable nor uncomfortable
(3) slightly uncomfortable
(2) uncomfortable
(1) very uncomfortable

2. Breathability

(7) very cool / breathable
(6) cool / breathable
(5) slightly cool / breathable
(4) neutral
(3) slightly warm / nonbreathable
(2) warm / nonbreathable
(1) very warm / nonbreathable

3. Moisture Sensation in Ensemble

(7) totally dry
(6) slight dampness sensation
(5) beginning to sweat sweating
(4) feels mostly wet
(3) some sweat dripping down
(2) heavy sweat dripping down
(1) feels wet all over / profusely

4. Softness

(7) very soft
(6) soft
(5) slightly soft
(4) neither soft nor harsh
(3) slightly harsh
(2) harsh
(1) very harsh

Rate the degree to which you sense each quality:

Property	Totally	Mostly	Mildly	Slightly	No sensation
6. Tight	(1)	(2)	(3)	(4)	(5)
7. Heavy	(1)	(2)	(3)	(4)	(5)
8. Stiff	(1)	(2)	(3)	(4)	(5)
9. Sticky	(1)	(2)	(3)	(4)	(5)
10. Nonabsorbent	(1)	(2)	(3)	(4)	(5)
11. Nonbreathable (hot)	(1)	(2)	(3)	(4)	(5)
12. Damp	(1)	(2)	(3)	(4)	(5)
13. Clingy	(1)	(2)	(3)	(4)	(5)
14. Rough	(1)	(2)	(3)	(4)	(5)
15. Nonstretchy	(1)	(2)	(3)	(4)	(5)

Add voluntary comments:

Evaluator ID ___________ Ensemble ID _________ DATE ________________

Period 12: Following turnout suit donning/doffing and sitting at rest for 10 minutes

Select the one best response for each item.

1. Donning time:

2. Ease in Donning

(7) very easy
(6) easy
(5) slightly easy
(4) neither easy nor difficult
(3) slightly difficult
(2) difficult
(1) very difficult

3. Ease in Doffing

(7) very easy
(6) easy
(3) slightly difficult
(2) difficult

(5) slightly easy
(4) neither easy nor difficult
(1) very difficult

4. <u>Bulkiness with Turnout Suit on</u>

(7) very bulky
(6) slightly bulky
(5) bulky
(4) neither bulky nor light
(3) slightly light
(2) light
(1) very light

5. <u>Ease of Movement with Turnout Suit on</u>

(7) very easy
(6) easy
(5) slightly easy
(4) neither easy nor difficult
(3) slightly difficult
(2) difficult
(1) very difficult

<u>Add voluntary comments:</u>

Post Test Survey **(after wearing each ensemble and in comparison to your current daily uniform):**

1. **Rank the uniforms for each descriptor by placing a number by each garment ID.**

   1 = most and 3 = least

Inflexible	A _____B_____C_____
Smooth	A _____B_____C_____
Soft	A _____B_____C_____
Stretchy	A _____B_____C_____
Breathable	A _____B_____C_____
Sticky	A _____B_____C_____
Sweaty	A _____B_____C_____

2. **Rank uniforms according to your preference by placing a number on each ID.**

   1 = preferred and 3 = least preferred.

   A______ B______ C______

3. **Overall Fit Rating**

   (7) very loose
   (6) moderately loose
   (5) slightly loose
   (4) just right
   (3) slightly tight
   (2) moderately tight
   (1) very tight

4. **How often do you wear a uniform of this style/fit?**

   (5) never
   (4) only if I have to
   (3) sometimes
   (2) often
   (1) all the time

5a. **How close is the fit of this uniform to the fit that you typically wear?**

   (5) the fit is very different
   (4) the fit is fairly different

(3) unable to determine one way or the other

(2) the fit is fairly similar

(1) the fit is very similar

5b. If the fit is different, please elaborate:

6. How well do you like the comfort and wear qualities of your preferred test uniform compared to your own preferred uniform?

(5) I greatly prefer the test uniform to my usual uniform

(4) I sort of prefer the test uniform to my usual uniform

(3) The test uniform seems about the same as my usual uniform

(2) I sort of prefer my uniform to the test uniform

(1) I generally prefer my own uniform to the test uniform

7. Rate how important each descriptor term is to your "Overall Comfort Rating:"

Descriptor	Very Important	Important	Somewhat Important	Very Little Importance	Not Important
Tight	(1)	(2)	(3)	(4)	(5)
Heavy	(1)	(2)	(3)	(4)	(5)
Stiff	(1)	(2)	(3)	(4)	(5)
Rough	(1)	(2)	(3)	(4)	(5)
No stretch	(1)	(2)	(3)	(4)	(5)
Inflexible	(1)	(2)	(3)	(4)	(5)
Sticky	(1)	(2)	(3)	(4)	(5)

Descriptor	Very Important	Important	Somewhat Important	Very Little Importance	Not Important
Nonabsorbent	(1)	(2)	(3)	(4)	(5)
Nonbreathable (hot)	(1)	(2)	(3)	(4)	(5)
Damp	(1)	(2)	(3)	(4)	(5)
Clingy	(1)	(2)	(3)	(4)	(5)

8. Is there *anything* else that you would like to add? Please comment in the space below.

APPENDIX J: Human Subject Evaluation data

In addition to the data presented in the report obtained through the human subject wear evaluation, the following summary slides were also compiled to demonstrate some of the data in graphical form to illustrate the overall opinion and acceptability of the AMBER system compared to the cotton and Nomex® IIIA baselines outline in this report.

NC STATE UNIVERSITY

AMBER WEAR TRIAL SUMMARY

NC STATE UNIVERSITY

WEAR TRIAL NUMBERS

20 PARTICIPANTS RECRUITED

19 PARTICIPANTS COMPLETED WEAR TRIAL

7 EMS

12 FF

3 TEST GARMENTS WERE EVALUATED

100% COTTON

100% NOMEX IIIA

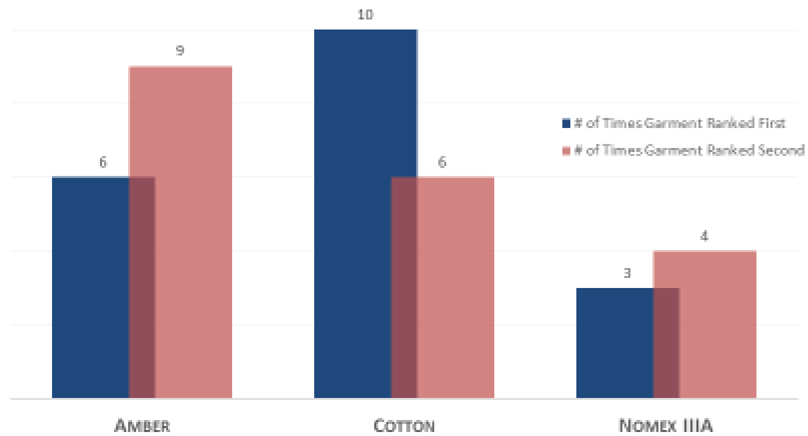
AMBER PROTOTYPE

NC STATE UNIVERSITY

WEAR TRIAL SUMMARY

OVERALL GARMENT PREFERENCE

During the post test survey, participants were asked to rank garments from Most Preferred (1) to least Preferred (3)

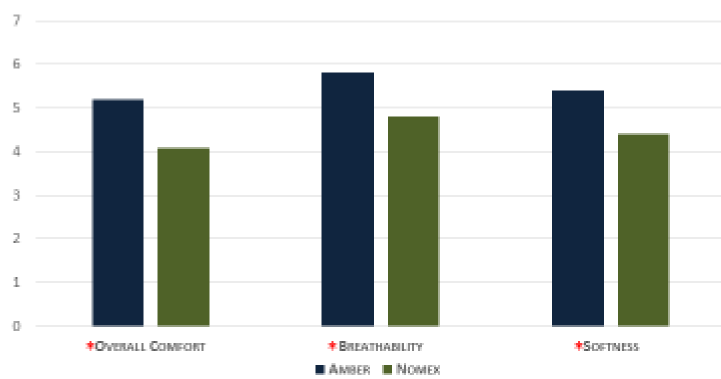


NC STATE UNIVERSITY

WEAR TRIAL SUMMARY

DONNING PERIOD: ENSEMBLE

RATING AVERAGES, N=19

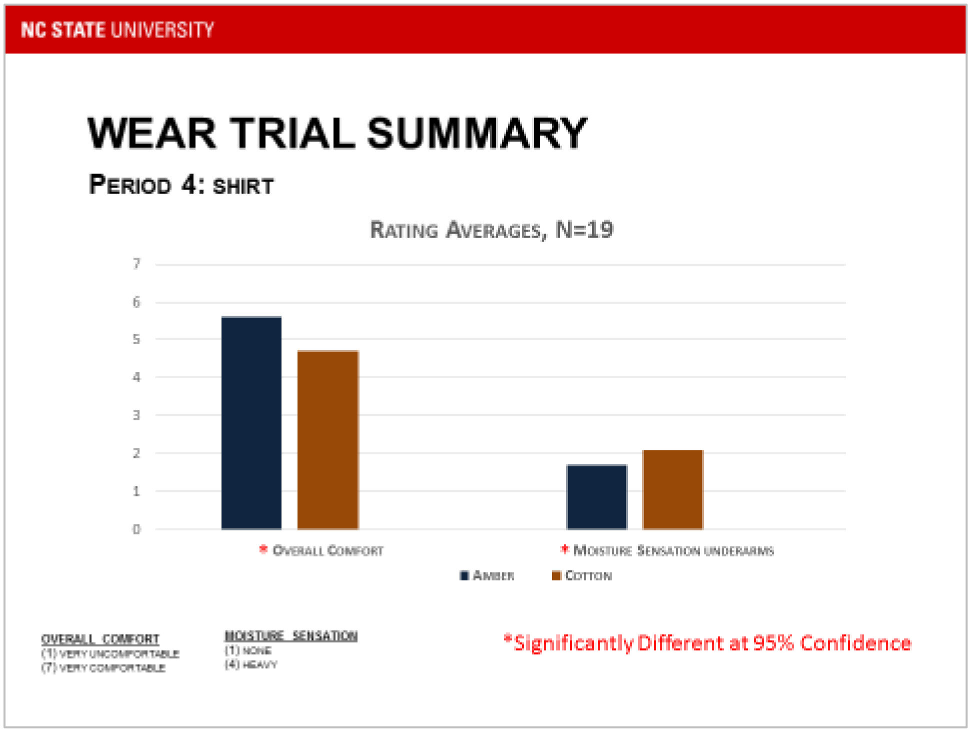


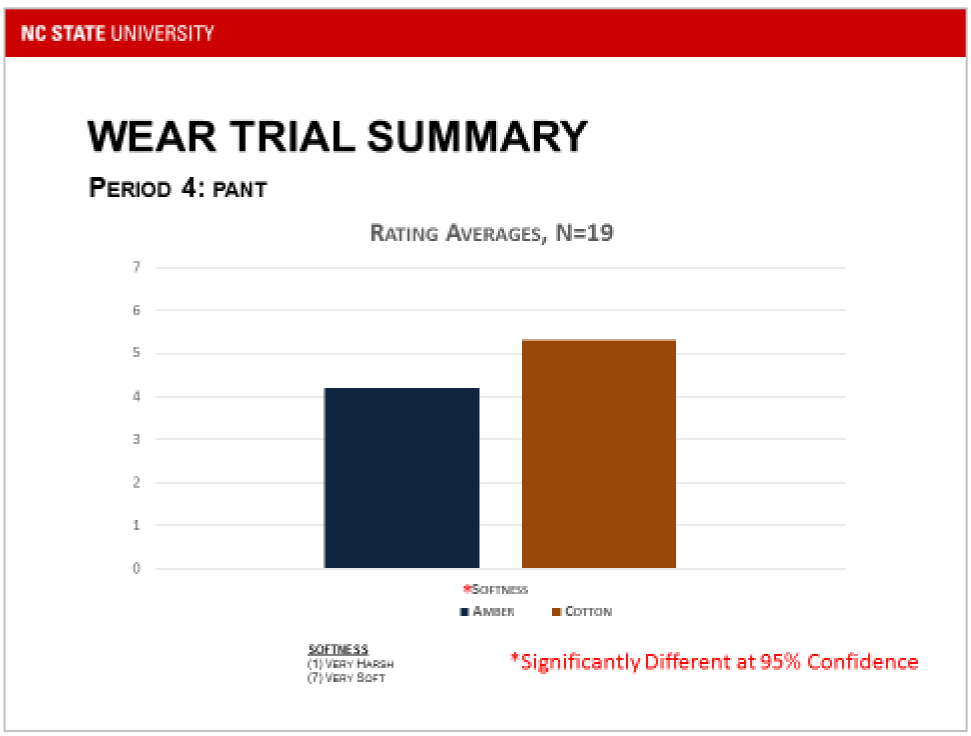
OVERALL COMFORT
(1) VERY UNCOMFORTABLE
(7) VERY COMFORTABLE

BREATHABILITY
(1) VERY WARM
(7) VERY COOL

SOFTNESS
(1) VERY HARSH
(7) VERY SOFT

*Significantly Different at 95% Confidence


NC STATE UNIVERSITY
WEAR TRIAL SUMMARY
PERIOD 4: SHIRT
RATING AVERAGES, N=19
7
6
5
4
3
2
1
0
* OVERALL COMFORT
* MOISTURE SENSATION UNDERARMS
AMBER
COTTON
OVERALL COMFORT
(1) VERY UNCOMFORTABLE
(7) VERY COMFORTABLE
MOISTURE SENSATION
(1) NONE
(4) HEAVY
*Significantly Different at 95% Confidence


NC STATE UNIVERSITY
WEAR TRIAL SUMMARY
PERIOD 4: PANT
RATING AVERAGES, N=19
7
6
5
4
3
2
1
0
*SOFTNESS
AMBER
COTTON
SOFTNESS
(1) VERY HARSH
(7) VERY SOFT
*Significantly Different at 95% Confidence

WEAR TRIAL USER COMMENTS

<u>Shirt</u>

- Zipper closure is good, but sticks out and rubs against throat/skin
- No stretch in collar
- Snaps are not great
- Comfortable, but due to size
- Feels warmer than others
- Sleeves are a bit short

<u>Pants</u>

- **Rough on knee**
- **Knee pads limit movement/too wide/too low**
- Knee area is bulky
- Pants are heavy
- Straps are not holding and awkward
- Do not like pockets on front of pant
- Zipper on leg feels harsh on skin

Note: This handful of comments were chosen from a larger pool of highlighted feedback on the AMBER wear trial prototype. These comments were all taken into consideration and used in the final iteration. These should be viewed as a tool used to optimize the design.

APPENDIX K: AMBER User Information Package

AMBER is

- A two-piece daily wear base ensemble made with FR materials, treated with durable water and oil repellency, and anti-microbial finish
- Knee pads designed with integrated impact, cut, and abrasion resistant materials, reinforced by membrane laminate for liquid penetration resistance
- Functional design features include:
  - Knit panels in shirt and trouser for improved fit and mobility
  - Trousers feature zipper openings for ventilation, reinforced seat for durability, quilted non-slip waistband for comfort and support
  - Shirt and trousers have deployable reflective trim

AMBER is NOT

designed to be a primary protective garment and should not be used to replace PPE used for emergency situations such as fire, chemical, biological, and ballistic threats.

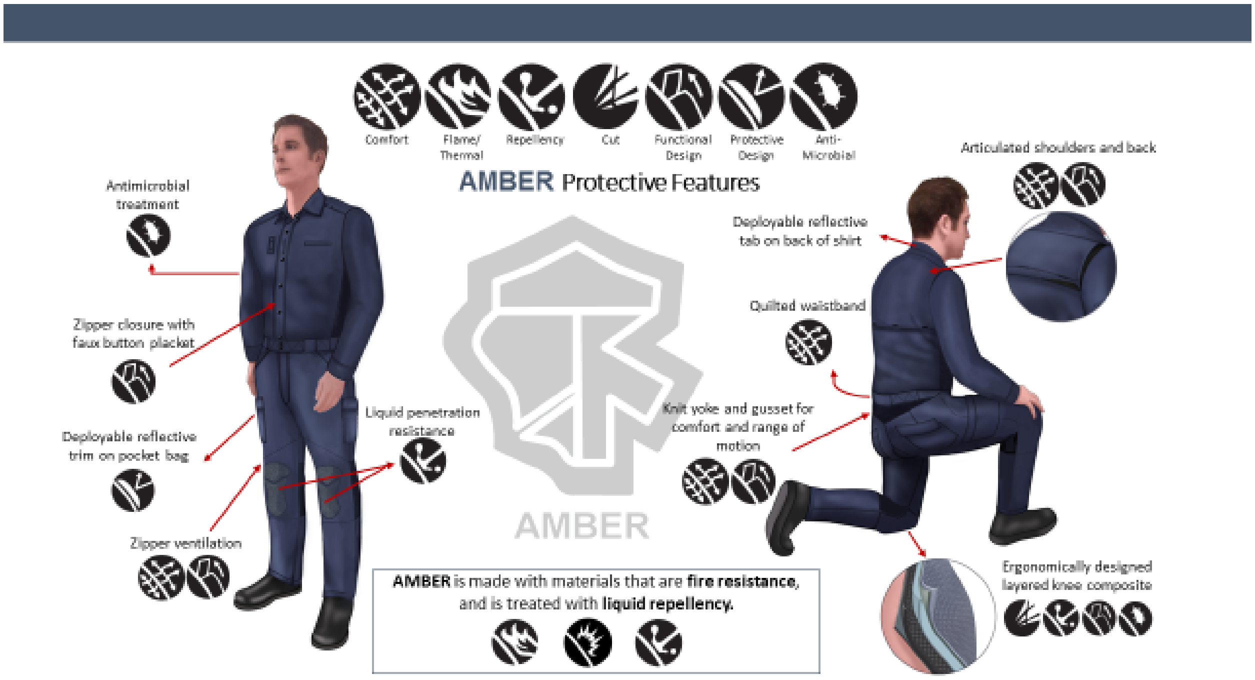
AMBER can

be used as a base component worn under a responder's primary PPE.

AMBER is certified to the base requirements of NFPA 1975 – 2014 edition, Standard on Emergency Services Work Clothing Elements

AMBER users should always use the garments in accordance with their own standard operating procedures for emergency response.

AMBER users should consult the attached user guide for information regarding caution and warning that pertain to the use of the garment.


Comfort
Flame/ Thermal
Repellency
Cut
Functional Design
Protective Design
Anti-Microbial
AMBER Protective Features
Antimicrobial treatment
Zipper closure with faux button placket
Deployable reflective trim on pocket bag
Zipper ventilation
Liquid penetration resistance
AMBER
AMBER is made with materials that are fire resistance, and is treated with liquid repellency.
Articulated shoulders and back
Deployable reflective tab on back of shirt
Quilted waistband
Knit yoke and gusset for comfort and range of motion
Ergonomically designed layered knee composite

References

1. **Department of Homeland Security.** *Project Responder 3: Toward the First Responder of the Future.* Science and Technology Directorate. s.l. : Homeland Security Studies and Analysis Institute, 2012.

2. —. *Project Responder 4: 2014 National Technology Plan for Emergency Response to Catastrophic Incidents .* Science and Technology Directorate. s.l. : Homeland Security Studies and Analysis Institute, 2014.

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