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## **Multifunctional Textiles for Advanced Personal Protective Equipment**

March 31, 2018

Sponsor

Department of Homeland Security

Science and Technology Directorate

Contract # 2014-ST-108-FRG002

Final Report for General Release

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Bryan E. Koene  
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Daniel Metrey  
Program Lead

The Contractor, Luna Innovations Incorporated, hereby declares that, to the best of its knowledge and belief, the technical data delivered herewith under Contract # 2014-ST-108-FRG002 is complete, accurate, and complies with all requirements of the contract.

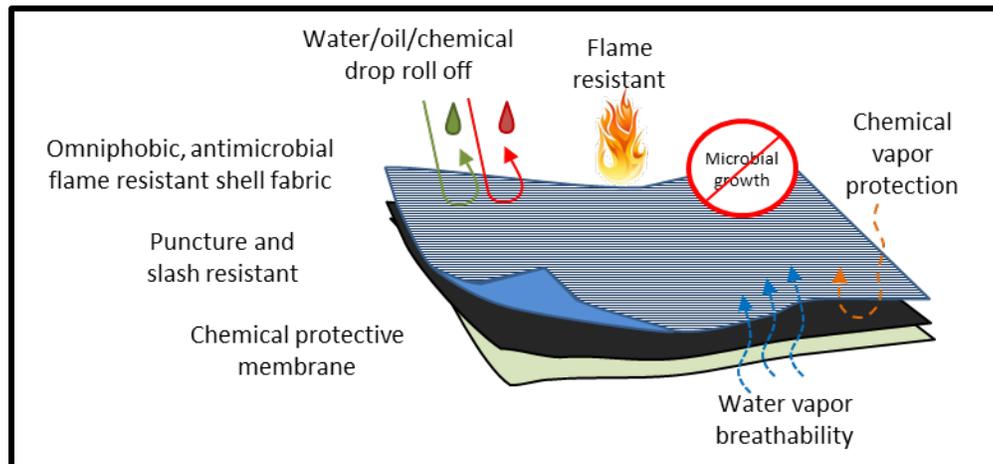
## 1. Introduction

First responders commonly enter situations with unknown threats wearing only duty uniforms. These uniforms offer little to no protection against atypical threats, causing the first responders to be exposed to unnecessary hazards. Multi-threat Personal Protective Equipment (PPE) for first responders, capable of withstanding chemical/biological, fire, stab and blast hazards, either do not exist in one garment or are bulky and unable to be worn at all times. Additionally, the cost of these PPE items is prohibitive to be used as duty uniforms. Multi-threat duty uniforms that are lightweight, breathable and can be worn at all times while providing protection against unanticipated threats are needed to address this capability gap.

Luna Innovations has designed an advanced uniform incorporating a suite of technologies that, when combined, will be able to provide a lightweight base garment ensemble that can be worn daily and will be capable of withstanding potential hazards for a limited period of time. The uniform will consist of:

- Omniphobic (fluid resistant) textile treatment for repellency against water, chemicals and bodily fluids;
- Antimicrobial textile treatment to protect against a range of bacteria and pathogens;
- Flame resistant cover fabrics;
- Chemical protective membrane in critical areas; and
- Cut and puncture protection layers in critical areas.

The uniform has been designed to meet National Fire Protection Association 1975 certification while providing the greatest benefit in terms of protection and comfort. Luna has partnered with Ultratech and Vertical Source to transfer the uniform designs from research directly to commercial production.



**Figure 1. Proposed Multi-Threat Protective Fabric for First Responder's Base Uniform**

## 2. Executive Summary

- Luna evaluated a wide range of state-of-the-art textile protective technologies for use with a first responder base ensemble uniform.
- Luna provided samples and participated in multiple technology demonstrations and discussions with the Department of Homeland Security (DHS) Science and Technology Directorate (S&T) and practicing first responders to aid in the development of a uniform.
- Luna developed a base ensemble uniform that can be worn daily that incorporates advanced fluid, chemical, fire and cut/puncture resistant properties.
- Luna partnered with Vertical Source, Inc. to transition the design for production, have the design certified to the National Fire Protection Association (NFPA) 1975 standard and to fabricate prototype deliverables.
- Over 250 NFPA 1975 certified prototype garments were delivered to the DHS S&T team for operational wear testing evaluations.
- The developed base ensemble uniforms are planned to be part of the Ergonomix commercial line manufactured by Vertical Source and their partners.

## 3. Program Objectives

As provided in the original proposal, Luna had four stated objectives for the project. All objectives were successfully met.

### 3.1. Objective 1 – Produce multifunctional textiles

Luna combined their aqueous based, solvent free, omniphobic textile treatment technology with chemical, wear, fire and cut/puncture protective fabrics to produce the base ensemble uniform. The result was a design that greatly enhances basic protection from the most common hazards encountered by a first responder.

### 3.2. Objective 2 – Validate textile properties

Textile properties were evaluated both by Luna and third parties. Furthermore, the uniform was certified to the NFPA 1975 standard by Underwriter's Laboratories (UL).

### 3.3. Objective 3 – Produce prototype textiles and uniforms

Over 250 NFPA 1975 certified prototype garments were delivered to the DHS S&T team for wear testing evaluations.

### 3.4. Objective 4 – Establish commercial partnerships and prepare for commercialization

Luna partnered with Vertical Source, Inc. to transition the design for production, have the design certified to the National Fire Protection Association (NFPA) 1975 standard and to fabricate prototype deliverables. Per the NFPA 1975 standard, all production, bill of materials and performance specs have been completed. Commercially available uniforms are planned to be part of the Ergonomix commercial line manufactured by Vertical Source and their partners, and are expected to be available to first responders by 2019.

## 4. Technical Development

### 4.1. Cover Fabrics

#### 4.1.1. Candidate Fabrics

Through communication with Tencate, ITG and Milliken, a list of commercial fire resistant (FR) fabrics was compiled for potential use with the base ensemble uniform. The selected 'cover fabric' candidates were evaluated for fluid repellency, flame resistance, tensile strength and tear resistance both before and after application of Luna's baseline Ultra EverShield® fluid repellency coating.

#### 4.1.2. Flame Resistance Testing

Flame resistance testing was performed in accordance with the ASTM D 6413 standard. Each sample yielded an afterflame time, afterglow time and char length measurement. At least three samples of each material were evaluated per fabric direction. The results indicated that the Ultra Ever Shield does not seem to significantly affect flame resistance and virtually all the evaluated 'flame resistant' fabrics met the target criteria of  $\leq 2.0$  seconds of afterflame time and  $\leq 6.0$  inches of char length. These targets were selected based upon anticipation of the NFPA 1975 certification requirements.

#### 4.1.3. Tensile Strength Testing

Tensile testing was conducted in accordance with the ASTM D5034 standard and was conducted on the selected cover fabrics through 50 wash cycles. It was clear from the results that Luna's repellency coating does not negatively affect the tensile properties of the fabrics. There was generally little drop-off in tensile strength after 50 wash cycles for all the fabrics. All candidates (except one material in the fill direction) had strength above 50 pounds (lbs), which was considered a target threshold based upon previous Luna textile programs.

#### 4.1.4. Tear Resistance

ASTM D2261 tear strength (Tongue Procedure) through 50 wash cycles was also completed. Again, it was clear from the results that Luna's repellency coating does not negatively affect the tear properties of the fabrics. Some of the fabrics had tear strengths that fell shy of the targeted minimum 6 - 8 linear pound-force (lbf) threshold after prolonged wash cycles. However, it should be noted that this target was somewhat arbitrarily selected as a goal and performance near this value was deemed acceptable.

#### 4.1.5. Cover Fabric Down selection

A 5.7 ounces per square yard (oz/yd<sup>2</sup>) fabric was initially selected to be the cover fabric for the prototypes. With Luna's Ultra EverShield fluid repellency coating, the fabric met repellency (Section 4.2), fire resistance, tensile and tear protective requirements after extensive wash cycles. However, a conference call discussion with members of the DHS S&T First Responder Resource Group (Section 4.6.1.1) highlighted the desire that the heavier fabric should be used for the pants, yet a lighter and more comfortable material should be used for the shirt. A 4.5 oz/yd<sup>2</sup> variation of Milliken's CXP fabric became the leading candidate for the shirt. As part of related projects at Luna, this fabric had already been treated with Luna's Ultra EverShield fluid repellency coating and performed well.

During discussion with the manufacturer about procuring the heavier material for the pants prototypes, it became apparent that there were recent supply issues with the down selected material. Thus, Luna evaluated alternatives. Milliken CXP 4.5 (which was already a leading candidate for the lighter weight material for the body of the shirt) and CXP 6.0 eventually were selected, as they were available in matching navy and could both be utilized in the uniform. With Luna's baseline Ultra EverShield fluid repellency treatment, these fabrics demonstrated reasonable wash durability in previous testing. However, while evaluating the addition of a biocide ("biocide 2") in the Ultra EverShield treatment, it was found that incorporation of the additive significantly improved the oil and water repellency performance on the CXP fabrics through 100 washes. Results of this testing can be found in Section 4.2.1. The testing indicated that the CXP has superior performance to that of the originally down selected pants fabric. Quality control testing, conducted by a third party, confirmed Luna's results.

Mechanical evaluations of the CXP cover fabrics through 100 washes were completed. ASTM D5034 tensile and ASTM D2261 tear testing were performed on repellency (Luna's Ultra EverShield/biocide 2 formulation) treated 4.5 oz/yd<sup>2</sup> and 6.0 oz/yd<sup>2</sup> CXP fabric, as well as untreated 6.0 oz/yd<sup>2</sup> CXP fabric. These data are presented in Figure 2, Figure 3, Figure 4 and Figure 5. The results met program goals, which were for fabrics to have a tensile average peak load of 50 lbf or greater and tear strengths in the 6 - 8 lbf range

or greater. As expected, the 6.0 oz/yd<sup>2</sup> fabric had higher values than the lighter 4.5 oz/yd<sup>2</sup> fabric, and the warp direction outperformed the fill direction. The tear strength of the 4.5 oz/yd<sup>2</sup> fabric used for the shirts was not as critical as that of the 6.0 oz/yd<sup>2</sup> material, which was utilized for the pants. The data reaffirmed that the repellency treatment did not affect mechanical performance. The results were verified with third party data, although there were some variances in test methodology that prevented direct comparison. (Note that testing of the CXP cover fabrics used in the fabrication of the prototype deliverables is included in Section 4.4, which closely matches the trial data below.)

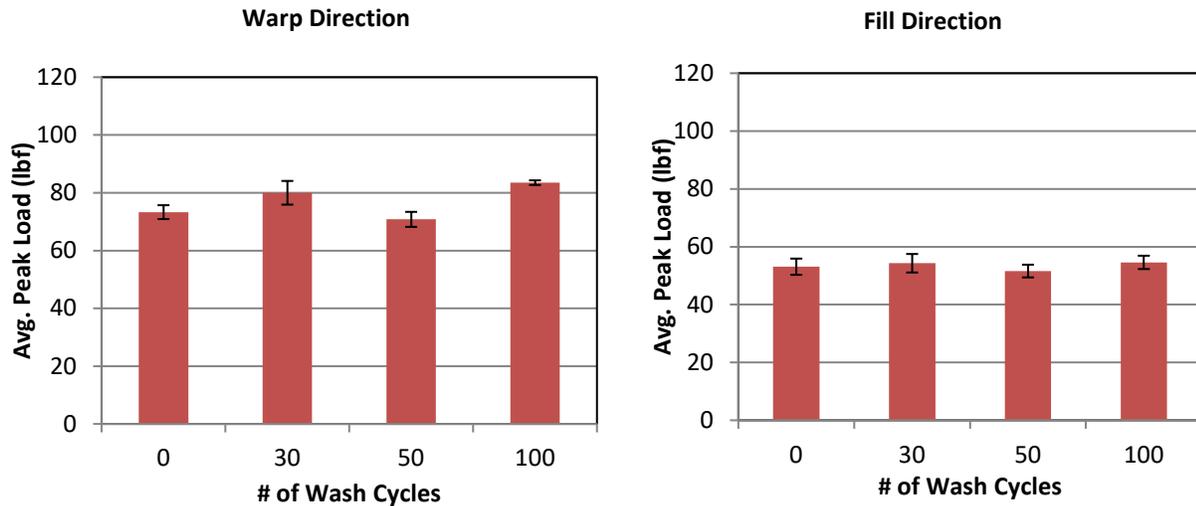


Figure 2. ASTM D5034 Tensile Data for Treated 4.5 oz/yd<sup>2</sup> CXP

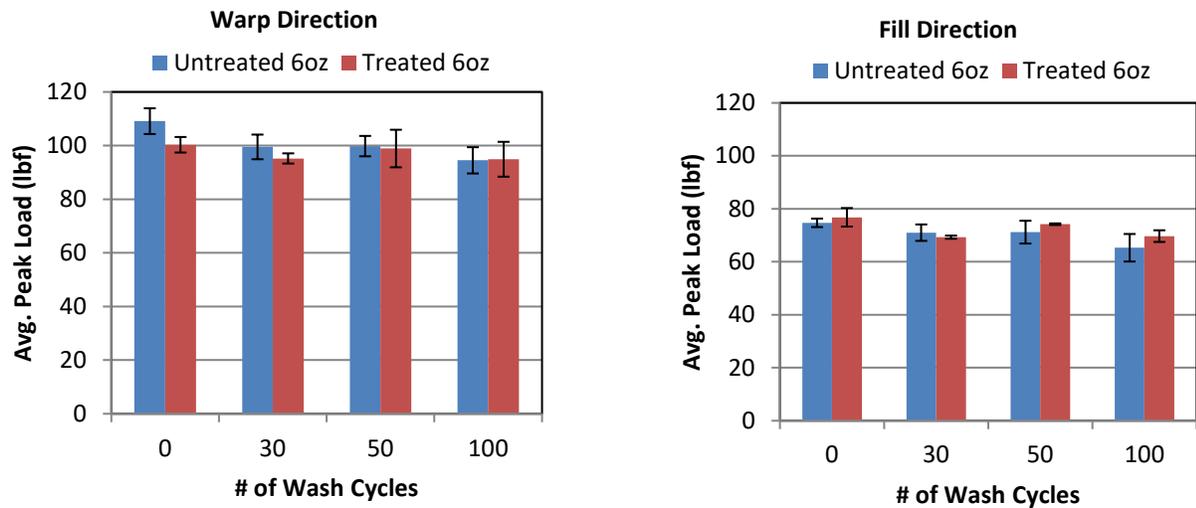


Figure 3. ASTM D5034 Tensile Data for 6 oz/yd<sup>2</sup> CXP

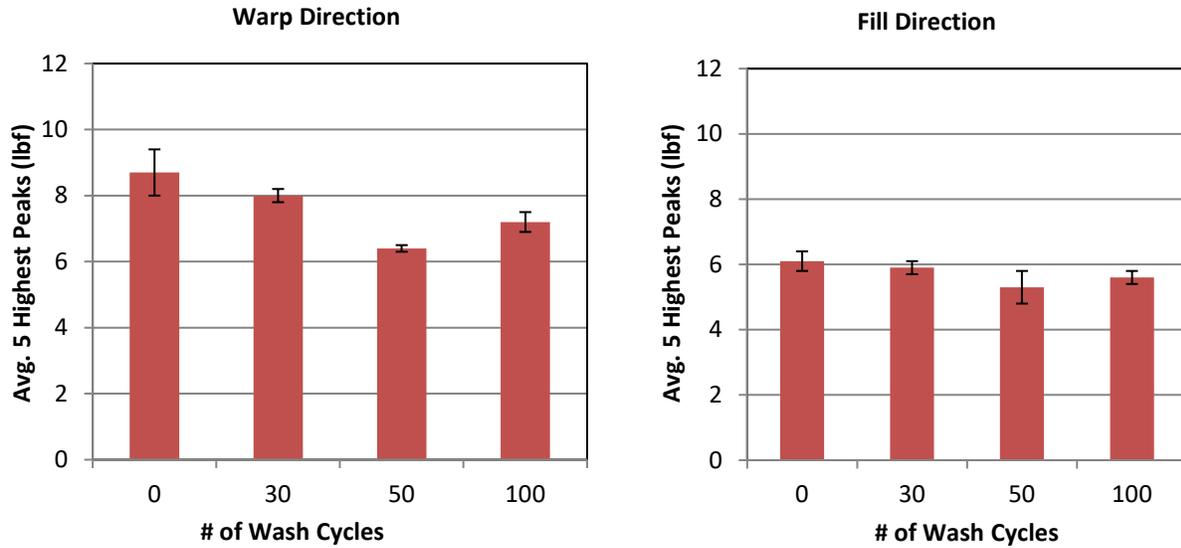


Figure 4. ASTM D2261 Tear Testing for Treated 4.5 oz/yd<sup>2</sup> CXP

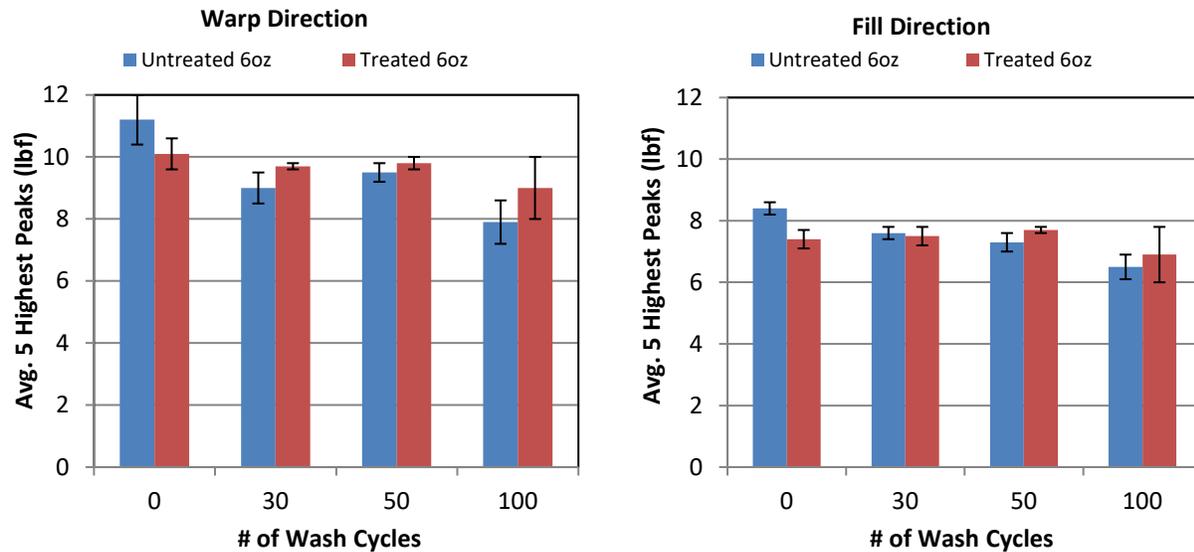
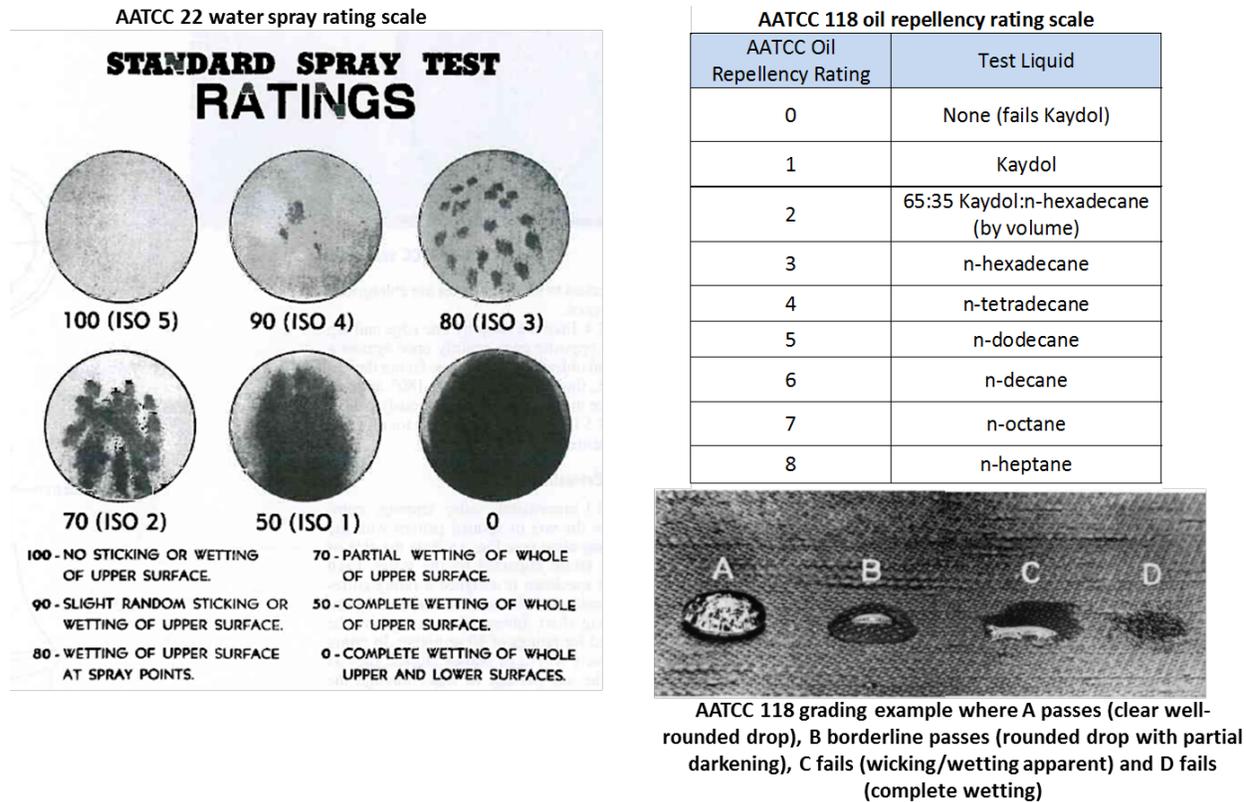


Figure 5. ASTM D2261 Tear Testing for 6.0 oz/yd<sup>2</sup> CXP

## 4.2. Fluid Repellant Treatment

### 4.2.1. Repellency

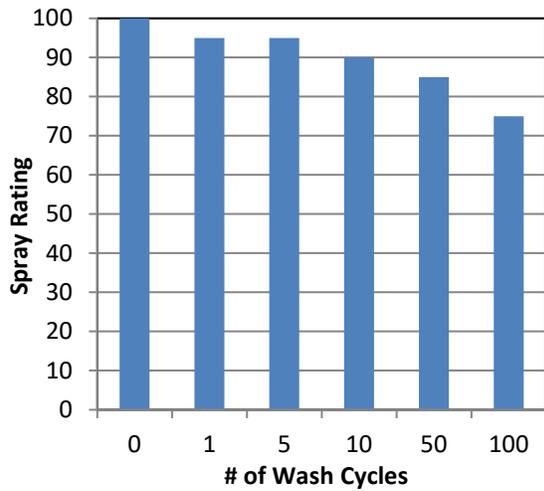
Initial candidate fabrics were coated with Luna’s Ultra EverShield fluid repellency coating and evaluated for wash durability via American Association of Textile Chemists and Colorists (AATCC) 22 water repellency and AATCC 118 oil repellency testing. For reference, an explanation of the rating system used in these tests is included as Figure 6.



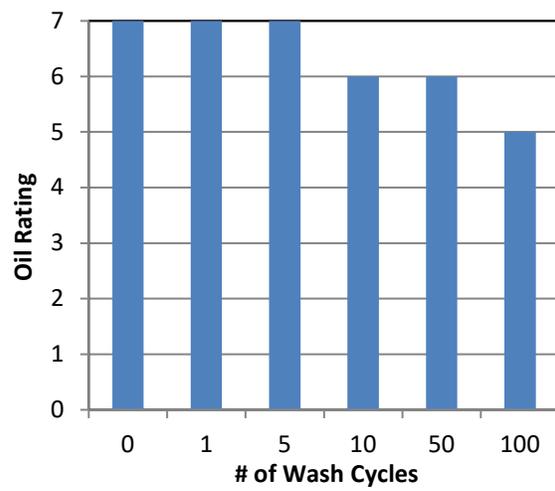
**Figure 6. Explanation of AATCC Water (AATCC 22) and Oil (AATCCC 118) Repellency Ratings**

Treated fabrics were evaluated through 100 cycles or until repellency dropped to near zero ratings. From the initial testing, a 5.7 oz/yd<sup>2</sup> candidate material was identified, which had superior performance in terms of retaining significant repellency protection after 100 washes. However, as described in Section 4.1.5, manufacturing supply issues were expected with the identified fabric and a lighter and more comfortable material was desired for the uniform shirt, which eventually lead (after evaluations were completed) to the down selection of the lighter Milliken CXP 4.5 oz/yd<sup>2</sup> for the shirt fabric and the heavier Milliken CXP 6.0 oz/yd<sup>2</sup> for the pants. A significant factor to this down selection was the fluid repellency of these fabrics. The CXP materials demonstrated reasonable wash durability in previous testing with Luna's baseline Ultra EverShield fluid repellency treatment, but the addition of an alternative biocide ("biocide 2") in the Ultra EverShield treatment was found to significantly improve their oil and water repellency performance through 100 washes, beyond that of the originally down selected pants fabric. Thus, CXP fabrics were sent to a commercial facility to apply the treatment in an industrial setting.

Thus, Luna completed repellency durability evaluations of the 4.5 oz/yd<sup>2</sup> CXP, 6.0 oz/yd<sup>2</sup> CXP, and laminate fabrics (Section 4.3) that were treated with Luna's Ultra EverShield/biocide 2 formulation. Graphs of these data are included in Figure 7, Figure 8 and Figure 9. These results were compared to results generated by third party testing and there was general agreement between the two data sets, both reflecting favorable oil and water repellent properties through 100 wash cycles.

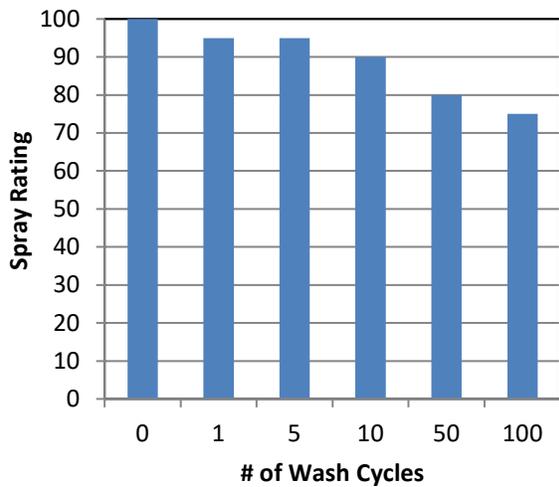


AATCC 22 Water Repellency

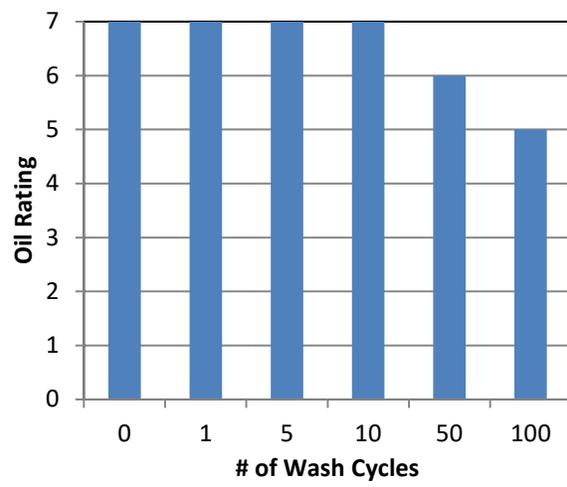


AATCC 118 Oil Repellency

**Figure 7. Wash Durability Data for Treated 4.5 oz/yd<sup>2</sup> CXP**

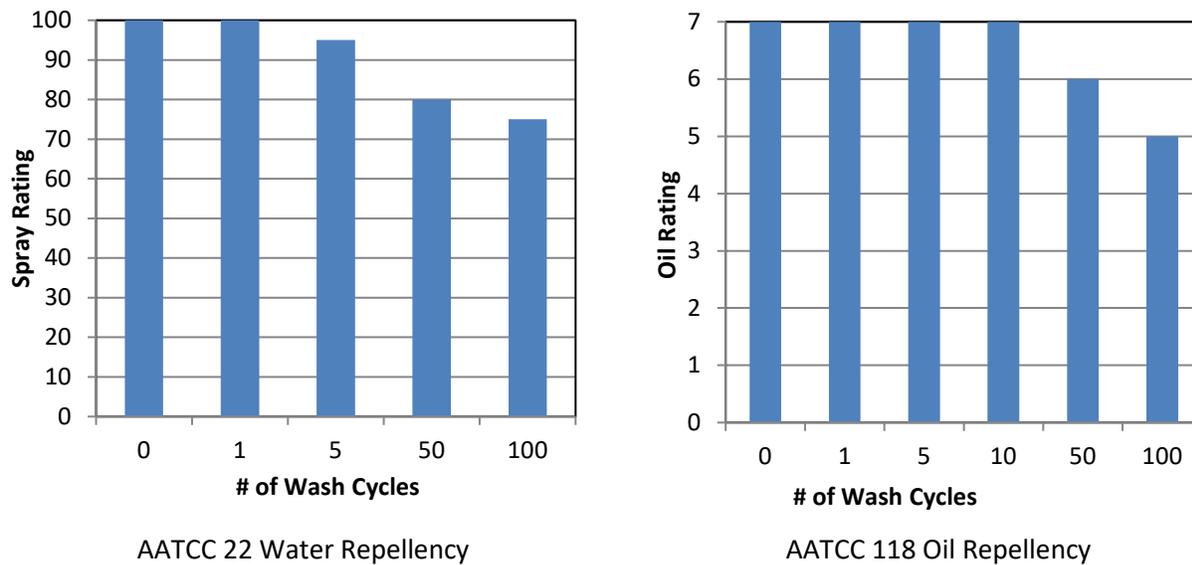


AATCC 22 Water Repellency



AATCC 118 Oil Repellency

**Figure 8. Wash Durability Data for Treated 6.0 oz/yd<sup>2</sup> CXP**



**Figure 9. Wash Durability Data for Treated Laminate Fabric**

#### 4.2.2. Antimicrobial

As noted above (Section 4.2.1), the addition of an alternative additive, designated “biocide 2,” demonstrated remarkable oil and water repellency when added to the baseline Ultra EverShield treatment on CXP fabric. This enabled the down selection of the CXP cover fabric. However, the addition of this biocide did little to increase the antimicrobial performance of the system.

In order to obtain both excellent wash durability and efficient biocidal activity, an additional biocide was incorporated into Ultra EverShield in combination with the biocide 2. This formulation was evaluated on 4.5 oz/yd<sup>2</sup> CXP for wash durability and antimicrobial properties. Results indicated good performance in killing Staphylococcal (Staph) bacteria. Unfortunately, the addition of the additional biocide lowered the water repellency, tested via AATCC 22, and the oil repellency, tested via AATCC 118, considerably. After 100 washes, the water and oil repellency ratings fell to 50 and 4 respectively, compared to the superior 80 (water) and 6 (oil) scores recorded for the formulation without the additive.

Luna looked at the possibility of adding reduced levels of the new biocide in the Ultra EverShield/biocide 2 treatment to allow for antimicrobial performance with minimal effect on repellency. These formulations (1032-091A-B contained varying levels of biocide 2 only, while C-E contained combinations of the new additive and biocide 2) were evaluated on 4.5 oz/yd<sup>2</sup> CXP for wash durability via American AATCC 22 (water repellency) and AATCC 118 (oil repellency) testing. As can be seen in Figure 10 and Figure 11, these formulations maintain reasonable oil and water repellent properties through 100 wash cycles. Thus, multiple variations of the additive and biocide 2 combination could be incorporated into EverShield without significant reduction in repellency.

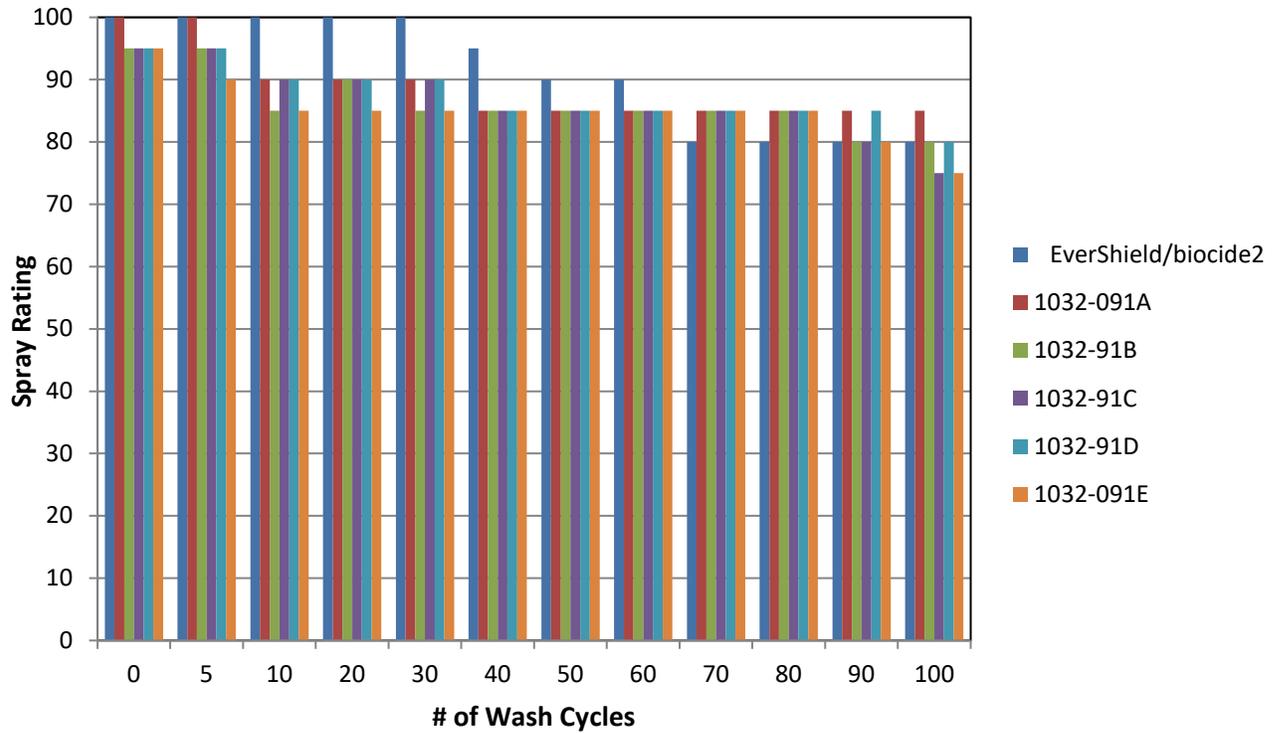


Figure 10. AATCC 22 Water Repellency Test Results

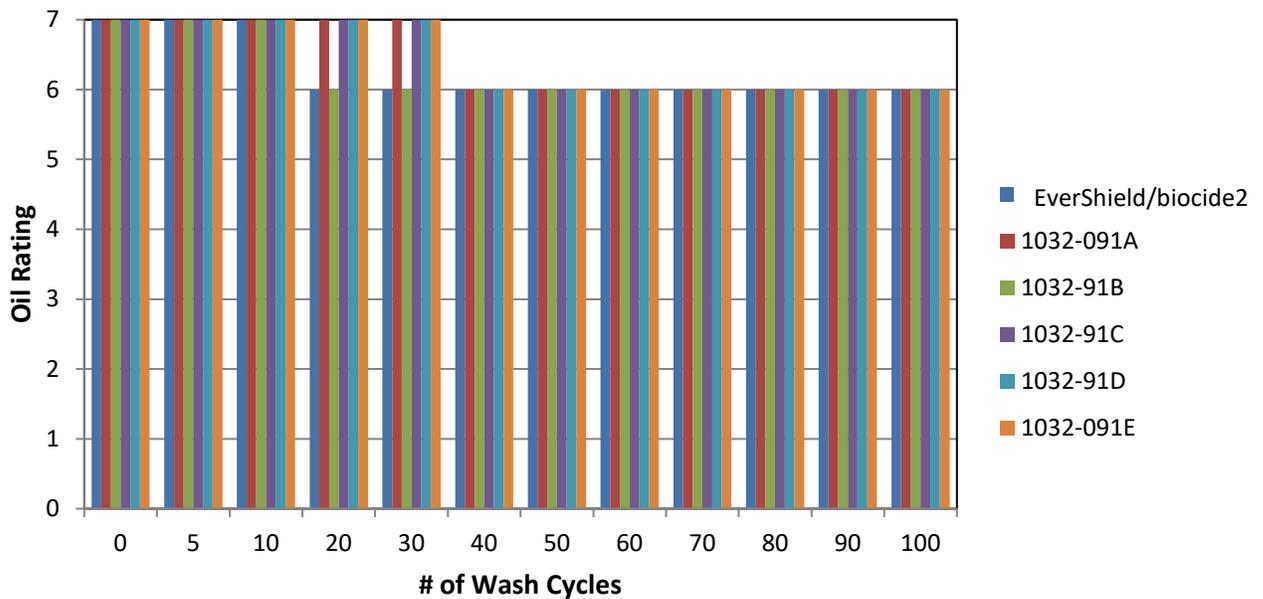


Figure 11. AATCC 118 Oil Repellency Test Results

These formulations were then tested on the 4.5 oz/yd<sup>2</sup> CXP for antimicrobial activity. Three sample growth plates (2X2 in) were evaluated with a 400 microliters (μl) inoculum of *Staphylococcus aureus* (*Staph*). Similar growth plates were evaluated with a 400 μl inoculum of *Escherichia coli* (*E.coli*). Significant log reduction against *Staph* was apparent in formulations that contained the additional additive (1032-091 C-E). The results demonstrated a minimum amount of the additive that is required for consistent

antimicrobial properties, with log reduction of 5 or greater against *Staph* through 30 wash cycles. These formulations also demonstrated variable log reduction against *E. coli*. The results verified that even high loadings of biocide 2 do not provide any antimicrobial benefit (formulations 1032-091 A & B did not have any log reduction). The data from the antimicrobial testing of sample 1032-091 E has been included as Appendix A.

#### 4.2.3. Repellency Formulation Down Selection

The above repellency and antimicrobial testing successfully demonstrated that it is possible to significantly reduce the additional biocide concentration in the formulation and still have efficient log kill against *Staph* (with variable log reduction against *E. coli*). Thus, antimicrobial protections could be incorporated without adversely affecting repellency properties. A formulation containing the biocide 2 and the minimum amount of the additional biocide required for consistent antimicrobial properties was down selected for use with the prototype uniforms. However, it should be noted that first responders are generally able to wash their uniforms with relative frequency when compared to other tactical uniform users, such as military personnel out in the field. Therefore, it is expected that the ability to wash the garment frequently and repeatedly with little loss in repellency will be more effective and relevant for antimicrobial performance than any biocide.

#### 4.3. Protective Membranes

Luna investigated the use of a breathable membrane material that could be laminated to uniform fabrics to provide a barrier to chemicals and biohazards (such as blood), yet still enable a degree of breathability. Although advanced technologies could be developed for the application, it was determined that pre-existing commercial products existed that would provide the protection desired and enable more rapid implementation.

An industrial scale production run of fire resistant laminated fabrics with membranes was conducted by one of Luna's commercial partners, which included treatment of the laminated fabrics with Luna's baseline Ultra EverShield fluid repellency coating. These layered fabrics generally consisted of a cover fabric, a Polytetrafluoroethylene (PTFE) non-porous membrane and a Nomex® backing layer all laminated into a single textile.

While the cover fabric material was expected to change, the membranes and laminated system configuration/production method were not. Extensive evaluations of these systems were tasked to Luna's commercial partner. The laminates were tested after wash cycles, after exposure to a wide range of materials (i.e., motor oil, jet fuel) and after abrasion evaluations. Of specific interest to the membrane technology was the hydrostatic resistance testing. In the ASTM D751 Mullen testing, which measures the resistance of material to water passage, all tests that included the non-porous membrane systems had values of greater than 45 psi resistance. Moisture Vapor Transfer, relevant to the ability of the material to release sweat, ranged from 600-800 grams per square meter in 24 hours ( $gr/m^2/24hr$ ) in ASTM E96 Upright Cup (water vapor) testing. These numbers were on par with measured values for Gore-Tex® and other related materials. The testing demonstrated that the laminated systems can be relatively comfortable, low weight, effective barriers.

A laminated material consisting of Milliken's CXP cover fabric (4.5 oz/yd<sup>2</sup>) with the PTFE nonporous membrane and Nomex jersey knit backing was selected for use with the prototype garments. Luna's partner produced this material and treated it with Luna's repellency formulation. Testing was performed by both the commercial partner and Luna on this material. Repellency data are presented in Figure 9 above. ASTM D5034 tensile and ASTM D2261 tear testing also met program goals (tensile and tear testing results on the laminate and cover fabrics used to produce the production uniforms are included in Section 4.4).

#### 4.4. Quality Control Testing of Prototype Uniform Fabrics

Quality control evaluations were completed on the 4.5 oz/yd<sup>2</sup> CXP cover fabric, 6.0 oz/yd<sup>2</sup> CXP cover fabric and laminate (consisting of 4.5 oz/yd<sup>2</sup> CXP cover fabric, a PTFE non-porous membrane and a Nomex backing) fabric that were produced for the base ensemble prototype deliverables. All fabrics were treated with Luna's down selected repellency system. The fabrics were evaluated for wash durability through 100 launderings via AATCC 22 (water repellency) and AATCC 118 (oil repellency) testing. Three samples from two different locations (6 total samples) within the production roll of each fabric were evaluated. Averaged data from these evaluations can be found in Figure 12 and Figure 13. The results indicate that the wash durability of the production fabric, in terms of the water and oil repellency, is slightly lower than that of samples generated via the application of the treatment in the laboratory. Samples of 4.5 oz/yd<sup>2</sup> CXP treated in the laboratory had initial water repellency spray ratings of 100, which dropped to 80 after 100 wash cycles. The oil repellency of the 4.5 oz/yd<sup>2</sup> CXP treated in the laboratory was initially a 7 and fell to a 6 by 100 cycles. These differences are not uncommon when treatment quantities are first scaled up for production runs using industrial equipment. However, it should be noted that the repellency durability is still considered very good and the production materials still passed the required NFPA 1975 Certification testing.

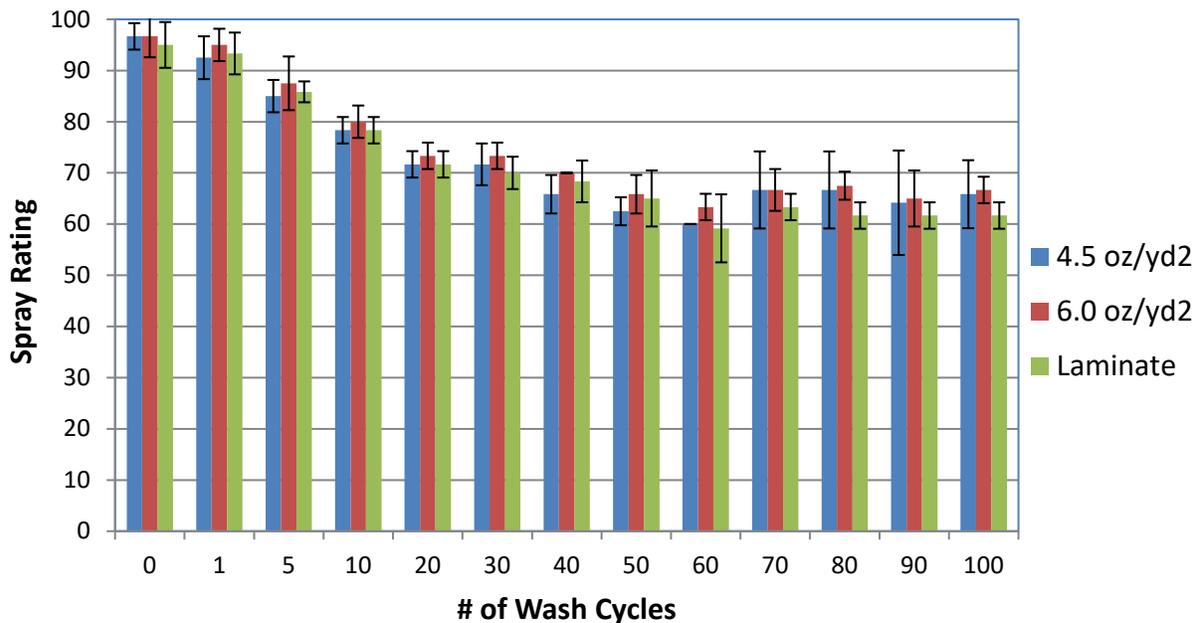
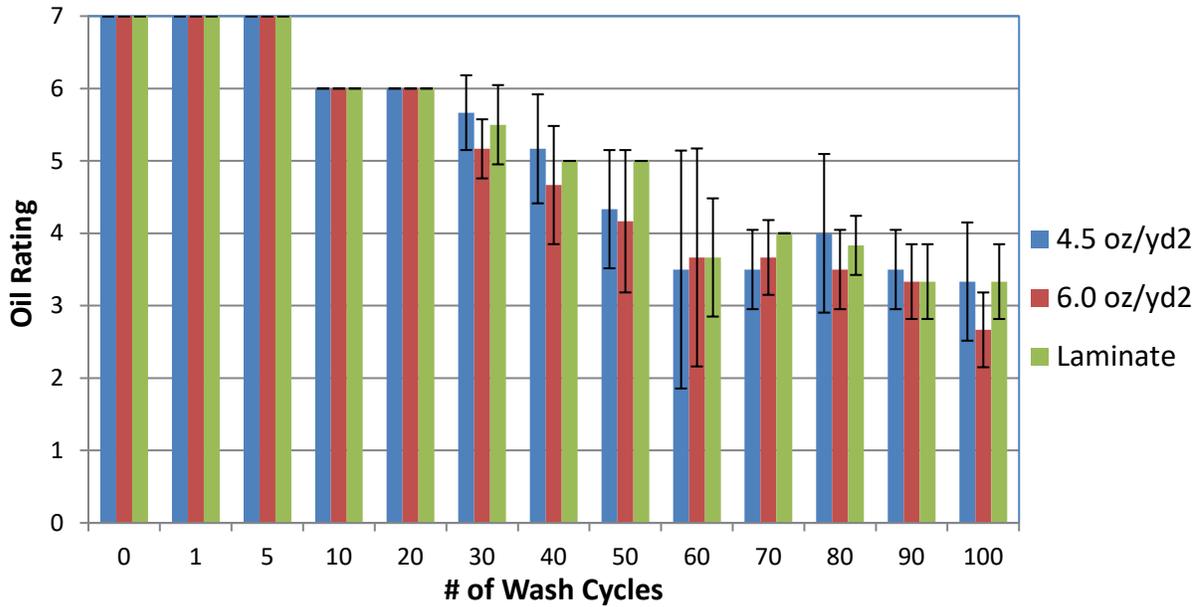
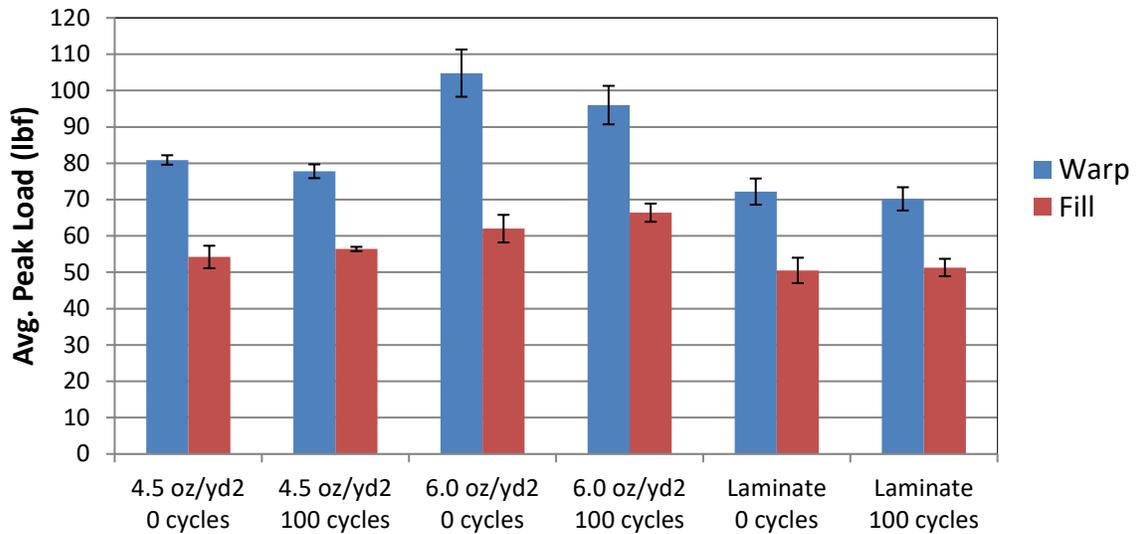


Figure 12. AATCC 22 Water Repellency through 100 Wash Cycles for Prototype Garment Fabric Treated at Industrial Facility in January 2016

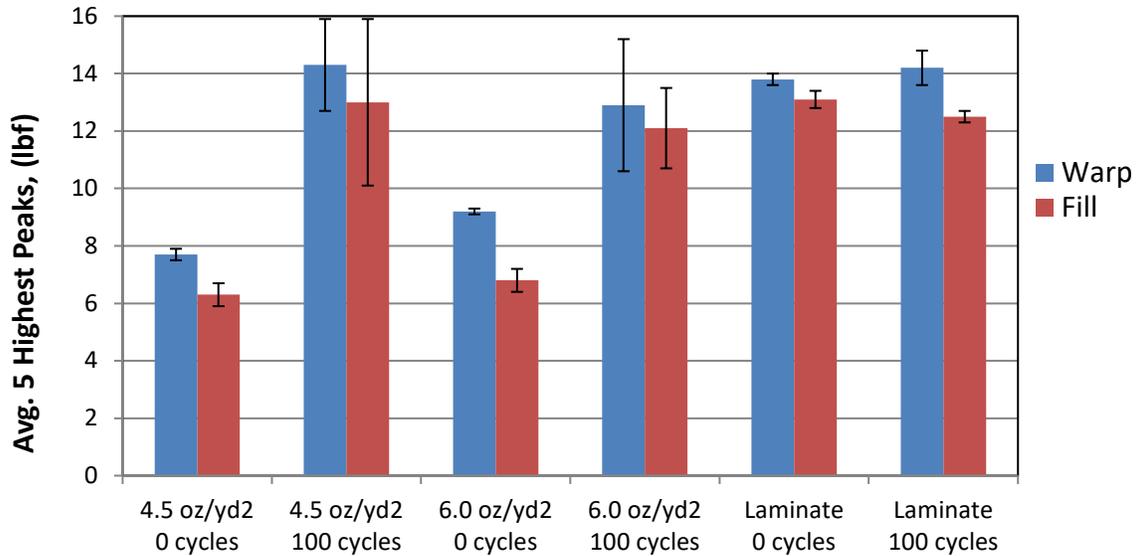


**Figure 13. AATCC 118 Oil Repellency through 100 Wash Cycles for Prototype Garment Fabric Treated at Industrial Facility in January 2016**

ASTM D5034 tensile and ASTM D2261 tear testing was also completed to verify that the prototype fabrics met program goals through 100 wash cycles. Average tensile peak loads of 50 lbf or greater and tear strengths in the 6 - 8 lbf range or greater were targeted. These data are included in Figure 14 and Figure 15.



**Figure 14. ASTM D5034 Tensile Results at 0 and 100 Wash Cycles for Prototype Garment Fabrics Treated at Industrial Facility in January 2016**



**Figure 15. ASTM D2261 Tear Testing Results at 0 and 100 Wash Cycles for Prototype Garment Fabrics Treated at Industrial Facility in January 2016**

As can be seen, all fabrics met target values in both the warp and fill directions. It is interesting that the tear resistance of both the 4.5 oz/yd<sup>2</sup> and 6.0 oz/yd<sup>2</sup> CXP cover fabrics increased after 100 cycles. This behavior was not seen with the laminate fabric, which had virtually the same tear resistance after 100 wash cycles. The tensile results for all fabrics remained consistent throughout the testing.

#### 4.5. Puncture/Stab Protective Fabric

A large body of data was collected in determining puncture and slash resistant materials for use with the base ensemble uniform. Originally, ballistic and full stab protection qualities were considered, although it was quickly determined that the amount of textile material or layers required to defeat such threats was not practical in a base ensemble uniform. Rather, puncture, in the case of resistance to needles and slash from a blade or sharp object, became the focus.

##### 4.5.1. Puncture Resistance Testing

The puncture resistance of fabrics was evaluated according to ASTM F1342 (Standard Test Method for Protective Clothing Material Resistance to Puncture) with the Test Method C probe. Target requirements were for candidate materials to withstand 9 pounds of probe force (linear pounds of force, lbf). A relative ranking of the ASTM F1342 puncture test peak load divided by areal weight (the weight of the fabric per unit area) was taken into account, as for a material to be a good candidate, it must have good performance, yet remain lightweight. From the results, the TurtleSkin<sup>®</sup> T9-1263 material performed the best at over 350 lbf/lb/ft<sup>2</sup>.

In discussion with first responders, puncture resistance from needles was determined to be of interest. Therefore, Luna modified their ASTM F1342 test fixture to accept hypodermic needles and evaluated the T9-1263 and other candidate materials, including advanced concepts such as shear thickening fluid (STF) impregnated fabrics. Results were normalized by dividing results by fabric areal weight to indicate performance per weight. Again, the commercially available Turtleskin T9-1263 proved to be the most effective at over 19 lbf/lb/ft<sup>2</sup>, especially when considering fabric weight.

#### 4.5.2. Stab Resistance Testing

Stab resistance testing was conducted in general concurrence with the National Institute of Justice NIJ-0115.00 E1/1 specification (strike energy of 17.7 ft-lbf, achieved by dropping a 4.2 lb mass/blade assembly a distance of 4' 2 1/2" onto the sample surface). Several commercial and laboratory fabricated materials were evaluated. Included in the testing were woven, knit and auxetic-knit (knit textiles that are designed to laterally expand when stretched) Kevlar® materials. The number of layers required to resist penetration for a given material was recorded. The number of layers was then multiplied by the material's areal weight for comparison. Thus, heavier materials requiring fewer layers could be compared to lighter materials, which required more layers. The best performing materials were again from TurtleSkin, including the T9-1263, requiring just under 0.6 lb/ft<sup>2</sup> to resist penetration from a P1 knife blade and just under 0.4 lb/ft<sup>2</sup> to resist spike penetration in the normalized NIJ-0115.00 E1/1 specification stab resistance testing.

#### 4.5.3. Slash Resistance Testing

Initial testing and discussions led to the understanding that protection from a slashing-type attack is a more appropriate need for a base ensemble uniform. A garment meeting National Institute of Justice NIJ-0115.00 E1/1 specification for a direct knife or spike attack (strike energy of 17.7 ft-lbf, achieved by dropping a 4.2 lb mass/blade assembly a distance of 4' 2 1/2" onto the sample surface) would require over 8 layers of the current best performing material. Furthermore, as discussed in a First Responder Resource Group conference call, law enforcement personnel are typically wearing vests to protect vital areas where stabbing is a major concern. However, slashing wounds are more frequent and typically occur on the extremities.<sup>1,2</sup> First responders are also likely to encounter non-direct slash-type hazards, such as broken glass or punctured sheet metal. Therefore, Luna evaluated slash resistant materials for inclusion into the base ensemble uniform.

A slash resistance test apparatus was constructed. The slash resistance test equipment was built under the guidance of Home Office Scientific Development Branch (HOSDB) 45/05, "HOSDB Slash Resistance Standard for UK Police." Essentially, this equipment is designed to drop an approximately 4.5 lb (2kg) mass holding a standard Stanley Model 1992 razor blade at a striking velocity of 19.7 feet/second (ft/s) (6 meters/second) at the test sample location.

Slash resistance testing was carried out on several materials, including knit Kevlar fabric samples. Each test was conducted with a fresh razor blade and the drop mass was released from the same height. The velocity was measured within one inch of the point of initial contact with the sample and was 15 ft/s with a maximum variation of 0.1 ft/s. The knit fabrics did not perform particularly well in resisting stab penetration by blade or spike (Section 4.5.2), but most performed well in the slash testing. One knit fabric performed extremely well, requiring only three layers to resist slash penetration. This knit fabric's low areal density is similar to woven Kevlar, adding the further potential for this fabric as a low-weight slash resistant layer. This fabric seemed to catch the blade and impede its motion more efficiently than other fabrics, resulting in a much shorter slash length in the contact layer. However, the knit materials did not perform as well in puncture and stab testing, while once again, the Turtleskin performed well in all evaluations. The Turtleskin T9-1263 required only a total areal density of 0.44 lb/ft<sup>2</sup> to impart slash resistance at the velocity of 15 ft/s (+/-0.1).

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<sup>1</sup> Horsfall, I. and Arnold, M., 'Protecting from Slash Knife Attacks,' Defence Academy of the United Kingdom, 2010.

<sup>2</sup> Bleetman, A., Watson, C.A., Horsfall, I. and Champion, S.M., 'Wounding Patterns and Human Performance in Knife Attacks: Optimising the Protection Provided by Knife-Resistant Body Armour,' Journal of Clinical Forensic Medicine 10: 243-248, 2003.

#### 4.5.4. Down Selection of Protective Materials

The TurtleSkin TU-1263 material was the most consistent and best performing commercially-available material for puncture, stab and slash testing. While other materials, such as the knit Kevlar and STF impregnated fabrics, showed promise, the technologies did not present a significant improvement or were not mature enough commercially to enable their use on the base ensemble prototypes.

#### 4.6. Uniform Design

##### 4.6.1. Design Evolution

###### 4.6.1.1. First Responder Resource Group (FRRG) Teleconference

An early teleconference with DHS S&T, Luna and selected members of the First Responder Resource Group (FRRG) was held on January 21, 2015. The goal of the meeting was to prioritize the most important requirements and to determine the best options for the configuration of the prototype deliverables. Key design considerations from that meeting are listed below.

- The uniform needs to be comfortable for standard wear (mission often requires considerable down time with the need to be immediately ready for action).
- The group is looking for something that would be appropriate for 70-80% of on-the-job activities/exposures.
- Battle Dress Uniform (BDU) style with pants and blouse are preferred.
  - A jacket would likely need to be specialized for specific functions and is probably outside the scope of the program.
  - Polo or tee shirts could also be considered.
- Several features were discussed.
  - Knee protection is important.
    - Knees are a high wear area (always on knees).
    - Knees are also a target area for extra biochemical resistance.
    - Larger knee area is desired than what is typical - protection is required from just below the knee to the upper thigh.
    - Perhaps extra protection could be replaceable (exposure also tends to break down garments that have extra protection in this area).
    - Padding for comfort is desirable.
- Fire resistance seems to be a requirement for all first responders.
  - Puncture resistance is important.
    - Hypodermic needle puncture is probably the biggest concern.
    - Responders can sit on needles.
  - Cut and tear resistance is needed (contact with sharp edges).
  - Comfort, breathability and thermoregulation are important.
  - Some ballistic protection should be considered for everyone (not just law enforcement), but it is understood that to meet most threats, this will require increased weight/cost.

- Consideration should be given for ability to quickly clean (on-site) with industrial wipes or similar items.
- General improvement over what is currently available is required.

#### **4.6.1.2. Phase I Review Meeting**

The Phase I Review Meeting was held on March 27, 2015, in Washington, DC. At that meeting, prototype design concepts based upon DHS S&T Phase I and FRRG input were discussed and demonstrated with conceptual mock-ups. Pertinent design related discussion notes are listed below.

- More permanent protection or protection systems that generally remained in place were preferable to insertable protective elements, such as the football pad concept, as there often is not time to insert the extra gear and it can easily be forgotten.
- DHS S&T liked the idea of having effective chemical protection in both the base layer and then having a removable cover as well.
- Specifics on preferable backside and arm protections would be best answered by FRRG members.
- A lighter weight shirt fabric compared with the pants may be desired for comfort.

#### **4.6.1.3. Teleconference with DHS and Members of FRRG**

A teleconference with DHS S&T, Luna and selected members of the FRRG was held on April 22, 2015, to discuss and select the most appropriate concepts for demonstration at the FRRG Annual Meeting.

#### **4.6.1.4. 2015 Annual FRRG Meeting**

Luna demonstrated program technologies and concepts at the Annual FRRG meeting on May 13, 2015, in New Orleans, Louisiana. A brief overview of the program was provided, followed by technology demonstrations of Luna's fluid repellent treatment, the STF technology for puncture resistance, and the base ensemble design concept mock-ups. The meeting was extremely valuable in enabling hands-on evaluation and discussion of the technologies and concepts. To generate feedback, a questionnaire was distributed to FRRG members that were present at the demonstration. DHS S&T tabulated the questionnaire results and feedback that was collected on Luna's concepts. This information was used in the design of initial preproduction prototypes.

#### **4.6.1.5. Meeting with Commercial Supplier of First Responder Uniforms**

Luna met with a commercial supplier of first responder uniforms on Thursday, June 4, 2015, to discuss integration of the potential designs for preproduction and deliverable prototypes. Although the company was not able to produce the eventual garments, many key design considerations came from the meeting. Most importantly, it was decided to use their popular selling designs as a starting point for base ensemble configurations. Although the base ensemble uniform would eventually evolve into a new design, it was important to establish a foundation.

#### **4.6.1.6. Preproduction Garments**

Preliminary designs for multiple preproduction garment options were drafted and a garment producer was contracted. The garments were manufactured for presentation to DHS S&T at the conclusion of Phase II in September 2015.

Luna coordinated with both the commercial supplier and uniform manufacturer to ensure that shirt and pants patterns and alteration tables were available. Luna also worked with the manufacturer to convey the advanced design concepts that had been developed over the course of the program. These concepts were finalized for the preproduction garments after consideration of the feedback from the FRRG Annual

Meeting questionnaire and further discussions with DHS S&T and Luna's partners. Three different pants and three different shirt concepts were manufactured.

#### 4.6.1.7. Phase II Review

A Phase II Final Review was held on September 11, 2015, with Luna, UK Home Office and DHS S&T representatives. Luna presented program progress, demonstrated down selected materials and delivered the preproduction uniforms. Three different pants and three different shirt variations were delivered, along with baseline commercial garments. The bulk of the meeting was spent demonstrating and discussing the preproduction garments. Focus Group evaluation plans were discussed.

#### 4.6.2. Focus Group Evaluation

Focus Group evaluations of various prototype garment concepts were conducted by DHS S&T on January 12, 2016, in Silver Spring, Maryland. Luna team members Daniel Metrey, Kate Annett-Hitchcock (NC State) and Paul Sander (UltraTech – part of the commercialization team) were present at the evaluations. DHS S&T's National Urban Security Technology Laboratory (NUSTL) administered exercise/movement instructions and a survey to the participants.

Six individuals were selected for the evaluation. Prior to manufacturing of the garments, DHS S&T provided Luna with the measurements of each participant. To simplify the testing, four concepts (two shirts and two pants) were down selected by DHS S&T from the original preproduction garments presented at the conclusion of the Phase II. A complete set was provided to each participant, totaling a total of 24 garments (12 pants and 12 shirts). A description of the Focus Group garments is below.

The pants were based upon a standard commercial pattern, which was altered to reflect the new design concepts. The pants had a second fabric layer of reinforcement at the knee and backside areas, multiple pockets in the thigh and hip area, fly front, and waistband elasticized for 6 inches on each side.

- **Pants Concept B:** Fixed Knee Protection. This concept utilized the standard size second layer reinforcement at the knees. However, a layer of Turtleskin was inserted and stitched down under the second layer. The second layer was fabricated from the laminate fabric.



Figure 16. Pants Concept B

- **Pants Concept C:** Detachable knee cover and backside reinforcement. A protective replaceable cover, longer and slightly wider than the existing knee reinforcement, was present with this concept. The knee areas had Velcro (no snaps) to lock the protective covers into place. Otherwise, the pants knee area was

standard. The covers contained a puncture resistant material (Turtleskin) between two layers of laminated material. In addition, the existing backside reinforcement layer was replaced by laminate fabric.



**Figure 17. Pants Concept C (Top: Detail of Velcro cover on the front of the leg; Bottom: Rear reinforcement)**

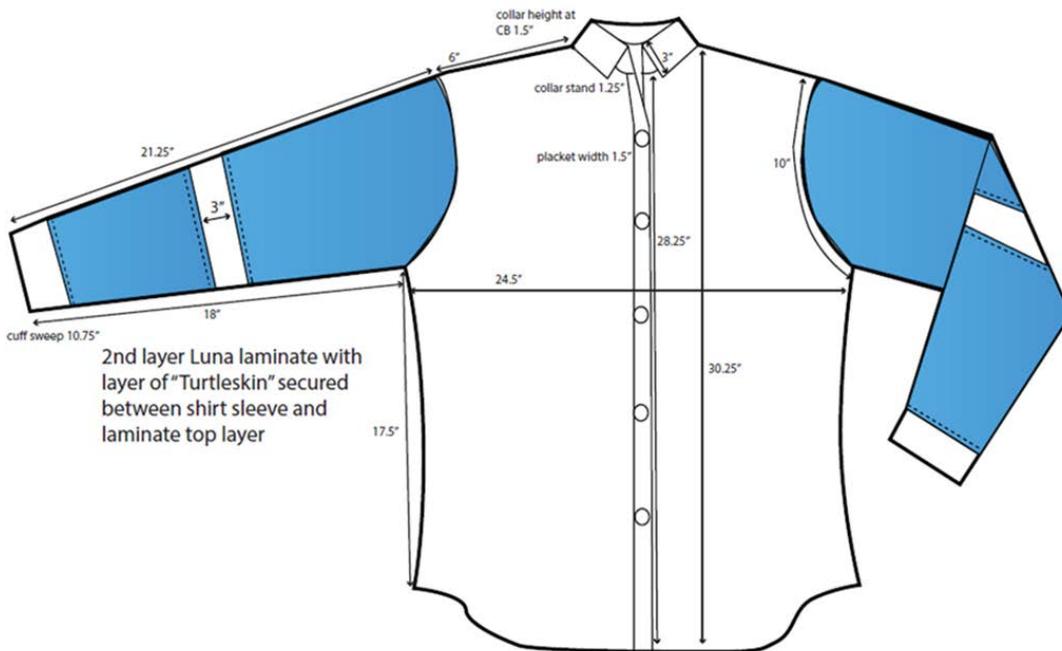
The shirts were also based upon standard commercial patterns, which were altered to reflect the new design concepts. The shirt concepts were completely based on sleeve modification (no modification to the body of the shirt).

- **Shirt Concept A:** The baseline pattern of this shirt had a mock button-up front, a longer tail in back, two zippered chest pockets, roll-up sleeve tabs and gusseted underarms. However, this design replaced the existing shirt sleeve with laminated fabric from the shoulder seam to cuff seam (both sleeves).



**Figure 18. Shirt Concept A**

• **Shirt Concept D:** This concept utilized the less complicated baseline design and maintained a lightweight shirt base layer for both sleeves. However, laminate fabric was added around the entire forearm and upper arm as second layers, leaving the elbow area free for articulation. A middle layer of Turtleskin was secured between the outer laminate and inner base shirt fabrics on the arms by stitching to provide a permanent layer of protection. A drawing of this concept is included in Figure 19.



**Figure 19. Drawing of New Shirt Concept D (dimensions may not be accurate)**

In general, the uniforms that were fabricated for the specific participants fit appropriately and were well received. DHS S&T sent Luna a preliminary draft of the January 2016 Focus Group report for adjudication. In addition, DHS S&T presented several of the Focus Group uniforms to a group of first responders assembled for a March 2016 presentation at DHS S&T's NUSTL. Combined, the feedback spanned multiple first responder groups, with the Focus Group consisting of firefighters, while the NUTSL presentation had law enforcement representatives. In both cases, the uniforms were generally well received and constructive input was provided.

#### **4.6.2.1. Final Design Development**

During a phone conversation on March 11, 2016, DHS S&T and Luna discussed the feedback and addressed differences in the preferences between the different types of first responders. For example, although firefighters do not have the same need for pocket space, it was determined that cargo pockets should remain in the basic uniform as they are preferred by Emergency Medical Technicians (EMT) and law enforcement personnel. After the phone conversation, Luna developed the design for the prototypes and submitted a PowerPoint summary to DHS S&T for review. Samples of a new shirt sleeve concepts were also sent to DHS S&T. DHS S&T comments were integrated into the final design.

On March 30, 2016, Luna officially entered into a subcontract with Vertical Source for the production of the prototype base ensemble uniforms. Vertical Source was subcontracted to provide a Technical Specification Package, NFPA Certification of the garments and all deliverable sets (one shirt and one pair of pants per set) of NFPA 1975 Certified Base Ensemble uniforms based upon the designs developed from the program. Vertical Source planned to be more than just the producer of the prototype uniforms. As the NFPA 1975 certification holder, they plan on actively marketing and selling the uniforms commercially.

#### **4.6.2.2. Final Design**

A general description of the final design follows.

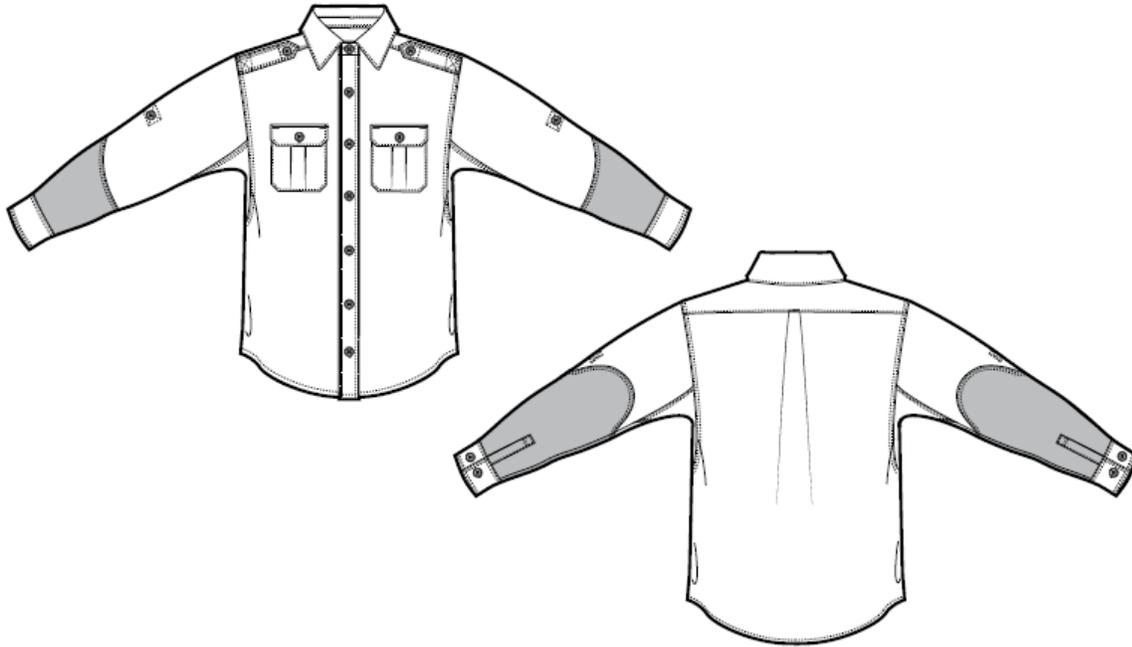
All fabric surfaces are treated with Luna's down selected Ultra EverShield based enhanced fluid repellency treatment. This treatment was optimized for use with the down selected prototype fabrics and provides both superior repellency and some antimicrobial protection. The basic pants fabric is the 6.0 oz/yd<sup>2</sup> Milliken CXP material and the body of the shirt is the lighter 4.5 oz/yd<sup>2</sup> Milliken CXP material. Laminated fabric, produced by a certified commercial supplier and consisting of 4.5 oz/yd<sup>2</sup> CXP cover fabric, a PTFE non-porous membrane and a Nomex<sup>®</sup> backing, is used as a 7.4 oz/yd<sup>2</sup> chemical resistant membrane barrier. This material is impermeable to liquids (water, blood, chemicals), but is water vapor (sweat) permeable, similar to GORE-TEX<sup>®</sup>.

The pants are modified from a popular commercial pattern, which have a second fabric layer of reinforcement at the knee area (into which padding can be inserted) and a large second layer of reinforcement on the backside (no flaps on back pockets). However, Luna modified the knee area. The second fabric layer at the knee is laminate material and extends (1 - 2 inches) further up toward the waist to provide chemical and biological protection. A layer of Turtleskin T9-1263 is inserted under the laminate fabric and stitched down, providing puncture/slash protection. The knee areas still allow for the insertion of extra padding, if desired. Extending the second layer at the knee required modification to the front cargo pocket design. The existing backside reinforcement layer is laminate fabric. Elastic remains at the waistband for comfort.

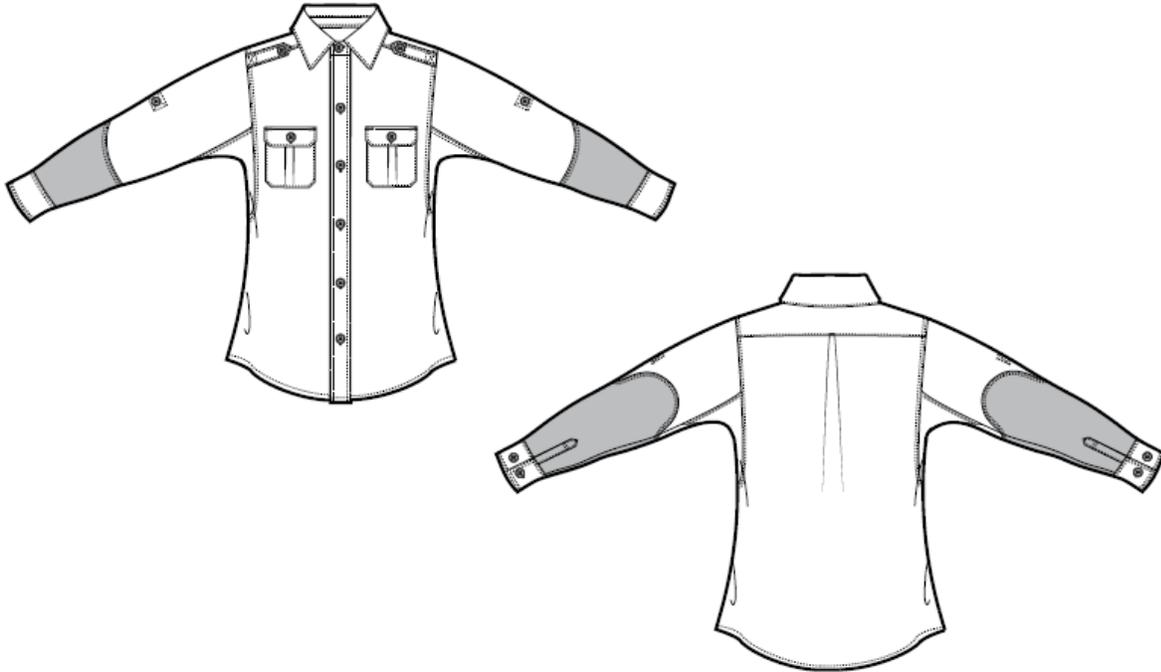
The shirt incorporates novel concepts developed for this program along with some existing elements from popular commercial shirt designs. The button-down shirt has gusseted arms and a pleated back for comfort. Front pockets flaps are secured with Velcro and no interior pockets are utilized (to minimize heat retention and cost). A new shirt sleeve concept was developed in which the forearm and elbow areas are protected by a second (outside) layer of laminate material providing a bio/chemical resistant barrier.

Turtleskin T9-1263 is included between the laminate and base (4.5 oz/yd<sup>2</sup>) fabrics on the forearm for puncture and slash protection.

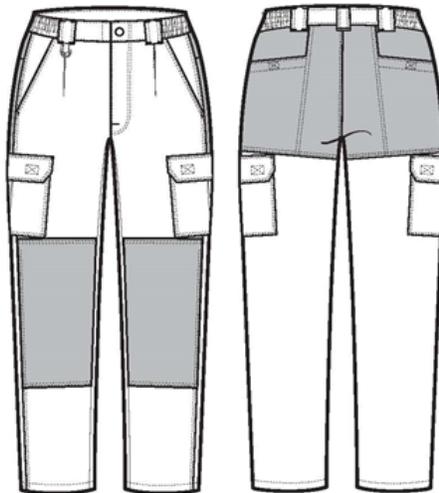
All designs were transferred to Vertical Source, who completed detailed Technical Specification Packages for the base ensemble prototype uniforms. These packages were used for NFPA 1975 Certification, prototype production and eventually commercialization. Specific sketches from each package have been included below as Figure 20 through Figure 23.



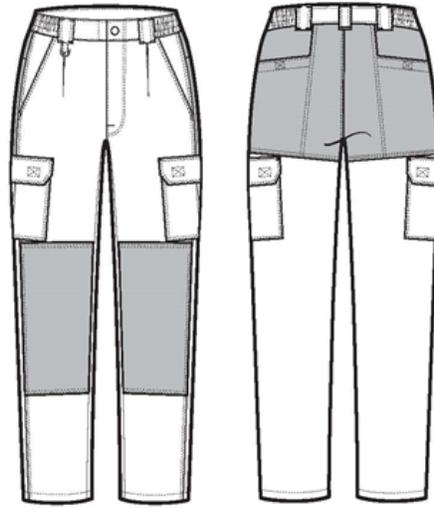
**Figure 20. Sketches of men's prototype base ensemble shirt. Shaded areas represent positioning of laminate/Turtleskin protective fabric.**



**Figure 21. Sketches of women's prototype base ensemble shirt. Shaded areas represent positioning of laminate/Turtleskin protective fabric.**



**Figure 22. Sketches of men's prototype base ensemble pants. Shaded areas represent positioning of laminate/Turtleskin protective fabric (Turtleskin is only utilized in knee area).**



**Figure 23. Sketches of women's prototype base ensemble pants. Shaded areas represent positioning of laminate/Turtleskin protective fabric (Turtleskin is only utilized in knee area).**

## 5. NFPA 1975 Certification

Luna worked with Vertical Source and Underwriters Laboratories (UL) to officially certify the designed base ensemble garments for NFPA 1975 compliance. NFPA 1975 certification was issued in August 2017, which enabled the production of the prototype deliverables.

## 6. Prototype Deliverables

A total of 250 NFPA 1975 Standard certified uniforms were deliverables for this project. Prototypes were manufactured for use with the DHS S&T Next Generation First Responder (NGFR) Apex Program's "Spiral 2" demonstration and for additional wear testing arranged by DHS S&T with first responders throughout the U.S. and with the UK Home Office.

The prototypes were manufactured by Vertical Source in Bangladesh at Crescent Fashion and Design Limited. Luna worked with DHS S&T and Vertical Source to ensure that properly sized garments were produced for specific wear testers when specified. For the remaining uniforms, a representative distribution of sizes (agreed upon by DHS S&T) was provided. Both men's and women's garments were produced. An outline of the distribution dates of these deliverables is below.

- 100 complete sets were delivered in August 2017 for the DHS S&T NGFR Apex Program's "Spiral 2" demonstration.
- 26 complete sets (1 extra) were delivered in August 2017 for UK Wear Testing.
- 30 complete women's sets were delivered to DHS S&T on December 5, 2017.
- 52 men's sets were delivered to DHS S&T on December 11, 2017.
- 37 men's shirts were also delivered on December 11, 2017.
- 6 men's shirts and 43 men's pants were delivered to DHS S&T on January 16, 2018.

## 7. Transition of Design for Commercial Production

From the start of the project, the importance of getting the developed designs available commercially for first responders was recognized. Thus, Luna partnered with Vertical Source, Inc. to transition the design for production, have the design certified to the NFPA 1975 standard and to fabricate prototype deliverables. Over 250 NFPA 1975 certified prototype uniforms were fabricated and delivered to DHS S&T and their partners for wear testing evaluations. The design is now available for production and commercially available uniforms are expected to be fabricated by the same company that produced the prototype uniforms. However, Vertical Source will utilize feedback from the wear testing evaluations to make any design modifications to the uniforms. If extensive design revisions are required, recertification may be necessary.

With the conclusion of Cooperative Agreement # 2014-ST-108-FRG002, the lead for transitioning the project to commercial production will transfer from Luna to Vertical Source and their partners. While Luna will remain in contact to provide support if needed, Vertical Source and their partners will control production and distribution.

NFPA 1975 Certification of the prototype uniforms required completion of the full production design, bill of materials and labeling specifications. Therefore, the uniforms are ready and have already been transitioned for commercial production. Vertical Source has been in the process of determining the optimal production and distribution logistics.

Vertical Source and their partners have incorporated a new company under the trade name Ergonomix (Figure 24). This company will include the base ensemble uniform as part of a new commercial product line. All corporate information and trademark filings have been submitted.



Figure 24. Ergonomix Logo

## 8. Appendix A – Antimicrobial Test Data

**Table 1. Antimicrobial Test Data**

1032-091 E		Program	3216.01	Date:	10/29/2015
Test Method	JIS Z 2801:21000	Test Sample Material	NYCO	Test Sample Size	5 x 5 cm
Species of Test Bacteria/Strain Number	<i>Staphylococcus aureus</i> ATCC 25923	Volume Test Innoculum	400ul	# Viable Cells of Bacteria in Test Innoculum	5.76 x 10 <sup>5</sup> (0w - 5w) 5.43x10 <sup>5</sup> (10w-30w)
<b>Sample ID</b>	<b>T=24 hours (CFU/ml)</b>	<b>Log reduction from Untreated Control</b>	<b>Notes</b>		
<i>Untreated Control</i>	TMTC	N/A log increase	Control has no inherent antimicrobial activity		
<i>1032-091 E - Initial</i>	No growth	5	No growth on any plates, full kill		
<i>1032-091 E - 1 wash</i>	No growth	5	No growth on any plates, full kill		
<i>1032-091 E - 5 wash</i>	No growth	5	No growth on any plates, full kill		
<i>1032-091 E - 10 wash</i>	No growth	5	No growth on any plates, full kill		
<i>1032-091 E - 20 wash</i>	No growth	5	No growth on any plates, full kill		
<i>1032-091 E - 30 wash</i>	No growth	5	No growth on any plates, full kill		

**9. Appendix B – Key Terms**

AATCC	American Association of Textile Chemists and Colorists
ASTM	Now ASTM International (formerly American Society for Testing and Materials)
FRRG	First Responder Resource Group
NFPA	National Fire Protection Association
PPE	Personal Protective Equipment
Areal Weight	The weight of the fabric per unit area
Cover fabric	Outer bulk fabric used for the uniform shirts and pants
Omniphobic	Fluid resistant (water, oil, etc.)
Warp direction	Longitudinal direction of fabric; warp yarns or other elements are stretched in place on a loom before the weft material is introduced during the weaving process
Weft direction	Transverse direction of fabric; weft yarns or other elements are drawn through and inserted over-and-under the warp yarns