PPE Cleaning Validation

Verification of Cleaning, Decontamination, and Sanitization of Fire Fighter Garments

SUPPLEMENT D: Evaluation of Outer Shell Liquid Retention Properties

Jeffrey Stull
International Personnel Protection Inc.
Austin, Texas

August 2019

NFPA RESEARCH FOUNDATION
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Part 5 of 9

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Final Report by:

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August 2019 (Part 5 of 9)

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Foreword

Fire fighter exposure to personal protective equipment (PPE) that is dirty, soiled, and contaminated is an increasing concern for long-term fire fighter health. Cancer and other diseases resulting from chronic exposures has become a leading issue and is presumed to be associated with fireground exposures relating to protection/hygiene practices and persistent harmful contamination found in fire fighter PPE.

While general cleaning procedures have been established in NFPA 1851, *Standard on Selection, Care, and Maintenance of Protective Ensembles for Structural Fire Fighting and Proximity Fire Fighting*, there are no requirements that demonstrate whether current cleaning practices will adequately remove contaminants from fire fighter PPE. Many manufacturer gear cleaning recommendations are vague and most cleaning product/process claims are unsubstantiated regarding contaminant removal effectiveness. Prior studies have identified persistent chemical and biological contaminants in structural firefighting PPE. Therefore, industry methodologies and practices are needed that can promote safe cleaning techniques so that fire fighters are not continually exposed to unclean or inadequately cleaned gear. It also important to set cleanliness criteria for the continued use of fire fighter protective clothing.

This project has established a relevant and credible procedure to validate "how clean is clean?" for fire service contaminated gear, and in doing so has addressed the primary goal of reducing fire fighter exposure to harmful contaminants in PPE. This includes the establishment of a repeatable and reproducible standardized method that can be used to determine the decontamination effectiveness of cleaning methods, and establish the needed fire service guidance for maintaining contaminant-free PPE as well as show that cleaning processes do not damage clothing. The project deliverables directly support efforts to update NFPA 1851 and other information that ensures consistent, effective cleaning processes of fire service gear.

This report is part five of a nine-part series on this topic of "PPE Cleaning Validation", with this part titled "*Supplement D: Evaluation of Outer Shell Liquid Retention Properties*". The following are all the reports in this series:

1. Master Report
2. Supplement A: Annotated Bibliography
3. Supplement B: Preliminary Work for Assessing PPE Cleaning Procedures
4. Supplement C: Investigation of Simulated Fire Ground Exposures
5. Supplement D: Evaluation of Outer Shell Liquid Retention Properties
6. Supplement E: Report of Semi-Volatile Organic Chemical Contamination, Extraction, and Analysis Procedures
7. Supplement F: Report of Heavy Metals Contamination, Extraction, and Analysis Procedures
8. Supplement G: Report of Biological Contamination, Extraction, and Analysis Procedures
9. Supplement H: Evaluation of Microbial Cleanliness of Selected ISP Advanced Cleaning Procedures

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Founded in 1896, NFPA is a global, nonprofit organization devoted to eliminating death, injury, property and economic loss due to fire, electrical and related hazards. The association delivers information and knowledge through more than 300 consensus codes and standards, research, training, education, outreach and advocacy; and by partnering with others who share an interest in furthering the NFPA mission. All NFPA codes and standards can be viewed online for free. NFPA's membership totals more than 65,000 individuals around the world.

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Abstract

Specific research was undertaken to determine the appropriate types of surrogate outer shell materials that should be used for cleaning verification. This investigation was deemed necessary to the project because a number of concerns arose as to what the suitable starting state and types of outer shell fabrics that should represent the wide range of different forms of fire fighter protective clothing. Different candidate materials having varying composition, structure, and liquid absorption/wicking properties were used during the initial development of cleaning verification procedures. These materials showed different affinities for absorbing inorganic chemical, semi-volatile organic chemical, and microbiological contaminants, which was an essential part of the cleaning verification test approach. Standardized tests were used to evaluate the physical properties and selected liquid absorption and wicking characteristics of these fabrics. These results were then contrasted to findings from testing outer shell fabrics samples from field exposed and laundered fire fighter clothing or samples of outer shell materials that were subjected to different numbers of laundering cycles. Tests from the collective sets showed varying levels of fabric absorption and wicking of different liquids ranging from high levels for untreated or highly used fabrics to relatively low levels for new or treated fabrics. On the basis of this investigation, specific decisions were made to use a conventionally finished outer shell fabric that would be washed multiple times to increase absorption of the different liquid contaminants and to more likely retain those contaminants during the cleaning verification procedures. A similar investigation also included related evaluation of a ballast fabric to be used in creating the laundry load during the cleaning verification process. This testing also qualified a low cost material that would have reasonable levels of liquid repellency to minimize cross contamination when used in the laundry load with contaminated samples.

Background

The proposed cleaning verification procedures are based on contaminating a representative fabric with a known amount of chemical or biological substances, subjecting fabric samples to the intended cleaning, and then extracting and analyzing any residual contaminants to determine the effectiveness of the cleaning process. The primary project objective was to initially apply cleaning verification to outer shell materials. Thus, a key consideration in setting up these procedures was to select an appropriate outer shell fabric for conducting this testing. It was decided that one fabric should be used because the cost of testing all fabrics could be considered prohibitive.

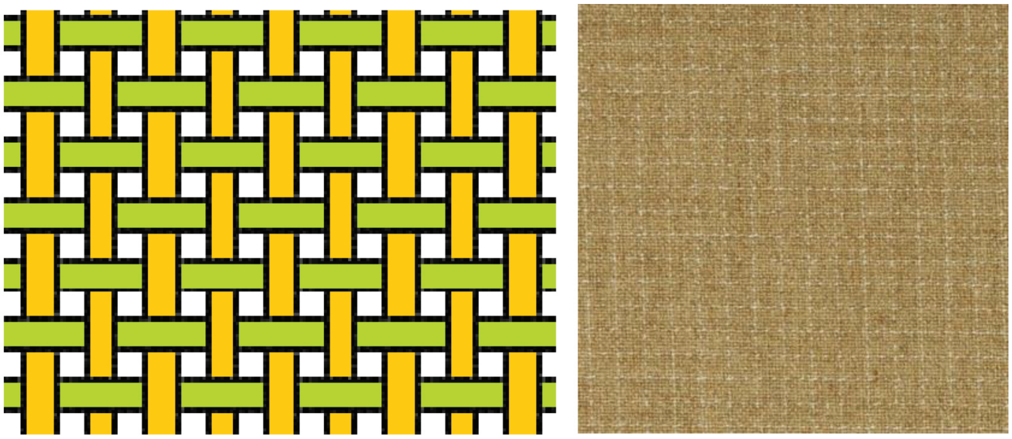
Outer Shell Fabric Selection Considerations

Choosing a suitable outer shell fabric that could be considered representative of all fabrics in the marketplace was a significant project challenge. This is because that at any one time, there are at least 15 to 20 different outer shell materials offered by the major fire service fabric suppliers. There are also several legacy outer shell fabrics that have been discontinued but remain in use for older clothing, which is still subject to periodic cleaning. There are several different variables that pertain to outer shell fabrics that include:

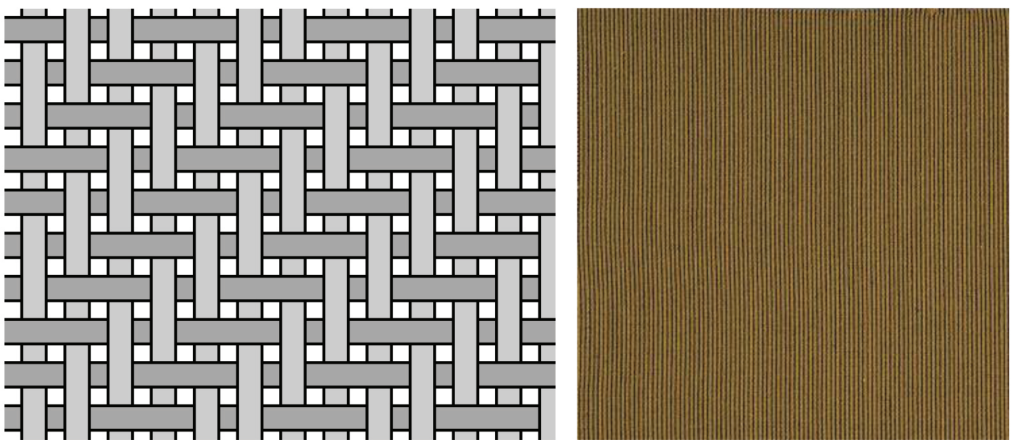
- Fabric fiber composition
- Fabric structure
- Fabric unit area weight
- Type of fabric finishes applied to achieve the required water absorption resistance

The majority of fire service outer shell fabrics are based on various meta- and para-aramid fibers and other specialty high temperature resistant polymers including PBI and PBO. These fibers generally have low liquid retention as compared to ordinary cotton. Nearly all fabrics are blended in fabrics and have different construction methods also, such as those shown in Figure 1.

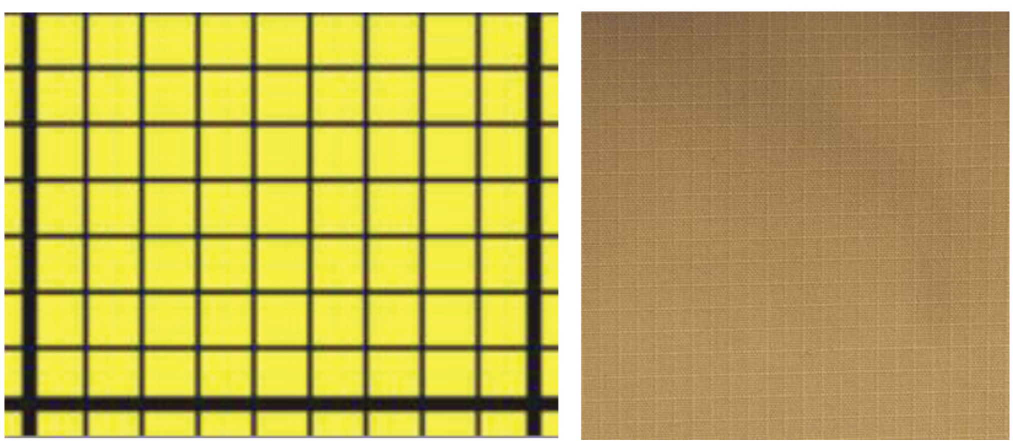
Figure 1: Sample outer shell fabric constructions



Plainweave Fabric



Twill Fabric



Ripstop Fabric

Fabric structure is important because the surface characteristics are dramatically changed by the type of weave that is used, and this can affect liquid absorption. For example, a plain weave fabric presents a relatively smooth uniform surface as do many twills. In contrast, a ripstop fabric construction creates raised fibers across the width and length of the fabric for creating increased material strength that also results in a less smooth fabric surface. Most outer shell materials weigh between 6 and 8 ounces per square yard because this is the unit area weight that generally yields appropriate levels of physical strength required by the NFPA 1971 standard. NFPA 1971 also requires minimum levels of water absorption resistance and thus, fabrics are treated with various finishes to repel water and other liquids. Therefore, all of these characteristics are generally known to influence the ability to introduce liquid contaminants uniformly onto and into fabric specimens intended for cleaning verification purposes.

Impact of Selected Contaminants

Specific contamination liquids have also evolved through the project based on the investigation of different fabric contamination approaches. Originally, it was the intent to use contamination techniques that mimicked how garments would be exposed under field conditions; however, due to the variability of these methods, eventually the decisions were made to proceed with more conventional laboratory processes by which small fabric samples would be doped with liquids containing the selected contaminants.

Three categories of contamination liquids were investigated in the project including semi-volatile organic compounds, inorganic heavy metals, and bacterial microorganisms. Each type of contaminant dictated different application liquids.

- Specific organic solvents had to be used for applying the selected semi-volatile organic compounds. These solvents had very low water solubility and tended to easily be absorbed by fabrics, even when finished.
- Heavy metals required an aqueous-based solution that was slightly acidic but nearer to the surface tension of water. These solutions would bead up on water-repellent finished fabrics.
- The biological contaminants also required a water-based solution that can contain certain nutrients that also were not easy absorbed by most conventional water repellent finished fabrics.

Therefore, while the organic solvent-based contamination solution was easily absorbed by the fabrics, it was much more difficult to get the water-based contaminant solutions for both metals and biological contaminants into the specimen uniformly. Consequently, two very different types of outer shell materials were used in initial experiments to characterize the ease of outer shell sample contamination:

- Fabric A (a 7.5 oz/yd^2 55% para-aramid, 37% PBI, 8% liquid crystal polymer, multi-filament ripstop outer shell material) with its conventional highly water-repellent finish was used as a representative standard outer shell fabric.
- A scoured version of Fabric B (a 6.6 oz/yd^2 60% para-aramid, 40% meta-aramid twill outer shell material) was used as a material sample more likely to absorb liquid and potentially represent outer shell fabric that had been washed multiple times and extensively used (whereby the finish was lost).

Scouring is a normal part of the textile preparation process for outer shells and other types of fabrics. In essence, it involves removing original process finishes from the fabric employed during the weaving process so that the material can more easily receive dyes for any intended coloration. After scouring followed by dying, water repellent finishes are normally applied. Therefore, the version of Fabric B used in this work was a preproduction sample of the fabric without any dyes or water repellent finishes.

Ballast Material Use

One other type of material necessary for the cleaning verification procedures was a ballast material. Ballast material was considered necessary because cleaning verification would be carried out using a regular laundry load, whereas contaminated outer shell fabric samples would be placed in surrogate clothing and the surrogate clothing items would then be combined with ballast material to make up the normal weight of the load. An extensive discussion of how the ballast material was used in the cleaning verification process appears in the primary report. For this study, it was important to ascertain the properties of the ballast material to understand whether the ballast material would absorb substantial amounts of liquid from the washing process and also be subject to cross contamination. Both attributes were seen as possible negative ballast characteristics during the laundering process since the intent of the procedures was to standardize as much of the wash process as possible. Another very important consideration was the relative cost of the ballast material since ordinary outer shell materials are relatively expensive and a considerable amount of ballast material would be needed to make up most laundry loads during cleaning verification. On the basis of a detailed industry fabrics review, a 10.2 oz/yd^2 100% polyester plain weave fabric with a 38 $\times$ 21 construction (Ballast Fabric) was separately selected based on its overall durability, physical properties, relative weight, and low cost. This material was subjected to a number of standardized industry tests to characterize its liquid absorption characteristics alongside the two selected outer shell materials and other clothing samples as described below.

Experimental Approach

General Evaluation of Outer Shell and Ballast Fabrics

The two candidate outer shell fabrics—Fabric A and scoured Fabric B—were tested for a number of common textile properties in accordance with standardized industry test methods that included:

- Unit area weight per ASTM D3776, Procedure C
- Thickness per ASTM D1777
- Thread count per microscopy method
- Breaking strength (grab) per ASTM D5034
- Tear resistance (trapezoidal) per ASTM D5587

Three other tests were also performed for assessing the ability to discriminate between fabrics with finishes versus those without. These tests included:

- Assessment of antibacterial finish efficacy per AATCC 100
- Absorbency of bleached textiles per AATCC 79
- Drying time per AATCC 199

The antibacterial test was conducted to assess the likelihood for the fabric to hold bacteria when inoculated and support continued bacterial growth after a period of time (without washing or sanitization). The absorbency test involved allowing a water droplet to fall from a fixed height and measuring the time for the droplet to fully absorb into the fabric. This test was run to determine if this method could show differences for how fabric samples might initially absorb water. Drying time was considered a relevant property because the process for contaminating fabric samples using aqueous samples could be affected, particularly if temperature restrictions in conducting the tests existed. The drying time test entailed immersing fabric specimens in water and then measuring the rate of drying based on the weight difference between specimen dry weight, wet weight, and wet weight after a 5 minute interval when exposed to a drying temperature of 37^{o}C.

The candidate ballast material was similarly tested for these same properties. The Fabric A outer shell and Ballast Fabric were tested after five laundering cycles performed according to AATCC 135 using the heavy/cotton wash cycle, a wash temperature of 60^{o}C, and heated tumble drying with a stack temperature of 66^{o}C.

Acquisition of Other Outer Shell Samples

The Project Team worked with a task group that was formed for the revision of NFPA 1851, specifically to address cleaning issues. This task group provided advice on various aspects of the cleaning verification procedures development. The group debated which of the outer shell materials should be used for purposes of cleaning verification and the state of the outer shell fabric in terms of its viable water absorption resistance as affected by prior washing. To help decide what fabrics would be representative, different participants in the process that included various independent service providers (ISPs) and clothing manufacturers were invited to provide sample garments that had been in the field, were used, and were cleaned, of varying age and materials. Alternatively, these participants were permitted to provide outer shell fabric samples that had been washed multiple times. On the basis of this invitation, seven organizations submitted 23 different samples. In general, samples for submitted garments were taken from same areas of garments, though, it is important to point out that "used" garments presented variable conditions of the sampled materials. Figure 2 shows sampling locations for a full coat and set of pants.

Figure 2: ISP provided coat and pants for sampling

A separate untreated cotton/polyester reference fabric was also added for baseline comparison purposes. The other ISP and manufacturer samples were also combined with candidate outer shell and ballast fabrics. These fabrics are listed in Table 1 (23 samples overall).

Table 1: Samples Subjected to Liquid Property Evaluations

Sample Designation	Type	Mfg. Date	Outer Shell*	Status	Number of Cleanings	Other History or Comments
Fabric B (Scoured)	Material only	N/A	Fabric B	N/A	None	
Fabric A (Pristine)	Material only	N/A	Fabric A	N/A	None	
Fabric A (Washed)	Material only	N/A	Fabric A	N/A	5	Washed per NFPA 1971
Cotton/Polyester	Material only	N/A	Cotton/Polyester	N/A	10	
Ballast Fabric	Material only	N/A	Polyester	N/A	None	
ISP #1-1	Coat	Oct-09	Fabric C	Retired	Unknown	Academy use
ISP #1-2	Coat	Jul-10	Fabric C	Retired	Unknown	Academy use
ISP #1-3	Pants	Jun-08	Fabric A	Retired	Unknown	Academy use
ISP #2-1	Pants	23-Jun-10	Fabric D	Spare gear	4	Typical soiling
ISP #2-2	Coat	May-14	Fabric E	Spare gear	3	Typical soiling
ISP #2-3	Pants	31-Mar-12	Fabric D	Spare gear	5	Just cleaned
ISP #4-1	Coat	3-Jun-09	Fabric D	In use	10	
ISP #4-2	Pants	21-May-09	Fabric C	In use	5	
ISP #4-3	Pants	7-Oct-08	Fabric F	In use	11	
ISP #5-1	Material only	N/A	Fabric A	N/A	20	Material only
ISP #5-2	Material only	N/A	Fabric D	N/A	20	Material only
ISP #6-1	Coat	1-Oct-06	Fabric I	Retired	Unknown	Donated
ISP #6-1	Coat	5-Jun-02	Fabric C	Retired	Unknown	Donated
ISP #6-1	Coat	Jul-95	Fabric J	Retired	Unknown	Donated
ISP #6-1	Pants	11-Oct-06	Fabric I	Retired	Unknown	Donated
ISP #6-1	Pants	Apr-07	Fabric J	Retired	Unknown	Donated
ISP #6-1	Pants	11-Jul-02	Fabric C	Retired	Unknown	Donated
Manfr. #1-1	Pants	Apr-09	Fabric C	Retired	Unknown	Beyond repair
Manfr. #1-2	Pants	Jun-07	Fabric H	Retired	Unknown	Beyond repair
Manfr. #1-3	Pants	Aug-10	Fabric A	Retired	Unknown	Beyond repair
Manfr. #2-1	Coat/Pants	Sep-16	Fabric B	Washed	40	Never used
Manfr. #2-2	Coat/Pants	Sep-16	Fabric E	Washed	40	Never used
Manfr. #2-3	Coat/Pants	Sep-16	Fabric G	Washed	40	Never used

*Fabric key is provided in Appendix B.

Application of Liquid Absorbency and Wicking Tests

All samples in this investigation were evaluated for the following properties:

- Water absorption resistance (NFPA 1971:2013, §8.25)
- Oil repellency (AATCC 118)
- Vertical wicking (PTL 1130)
- Horizontal wicking (AATCC 198)

These tests were performed for the requisite specified number of replicates. Table 2 provides a synopsis of the test procedures performed for each of the key evaluations. Photographs of these tests are included in Figures 3 through 6.

Table 2: Liquid Property Test Methods Used in Investigation

Property	Test Method	Description	Measurements
Water Absorption Resistance	NFPA 1971, Section 8.25 Based on modified AATCC 42	An 8″ square material sample was clamped in embroidery loop and set at an incline; 500 mL water was sprayed onto the sample from 0.6 m height; the sample was blotted and a 4″ × 4″ specimen was cut from the sample and weighed; the same specimen was allowed to completely dry and was reweighed.	Percent water absorption
Oil Repellency	AATCC 118	Droplets of different hydrocarbons of varying surface tension were applied to the test fabric and were observed for "wetting" fabric (as opposed to remaining as a 'bead').* The fabric was rated based on the liquid with the lowest surface tension that did not absorb into the sample.	Oil repellency rating (0 to 8; 8 is highest rating)
Vertical Wicking	PTL 1130**	The edge of a 1″ wide × 7.5″ tall specimen was suspended to touch a water reservoir. The height of water rise in the specimen was measured every 5 minutes and the total time to 15 cm was determined.	Vertical rise every 5 minutes through 30 minutes. Time to 15 minute vertical rise.
Horizontal Wicking	AATCC 198	A 1 mL volume of water was dispensed onto a horizontal fabric sample held in an embroidery loop that had been marked with a 100 mm diameter circle from the dropping center. The distance of horizontal wicking was measured along with the time of spread at 5 minutes.	Length and width of horizontal wicking distance (at 5 minutes); wicking rate

*Test liquids in decreasing surface tension are (1) Kaydol, (2) 65% Kaydol/35% n-hexadecane, (3) n-hexadecane, (4) n-tetradecane, (5) n-dodecane, (6) n-decane, (7) n-octane, and (8) n-heptane.

**Internal method for test lab—Precision Testing Laboratories (PTL).

Figure 3: Water absorption test method apparatus

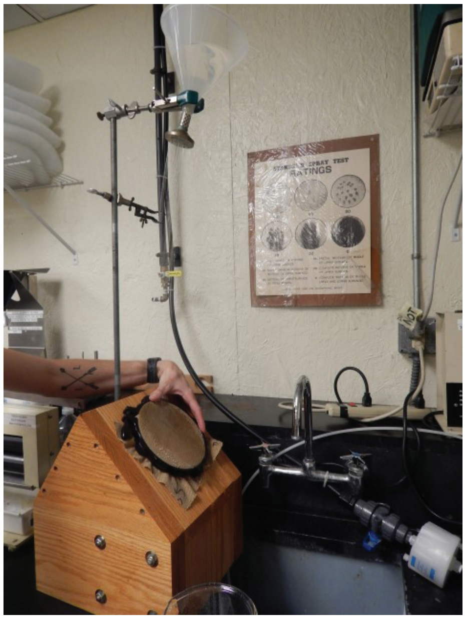


Figure 4: Oil repellency test set up

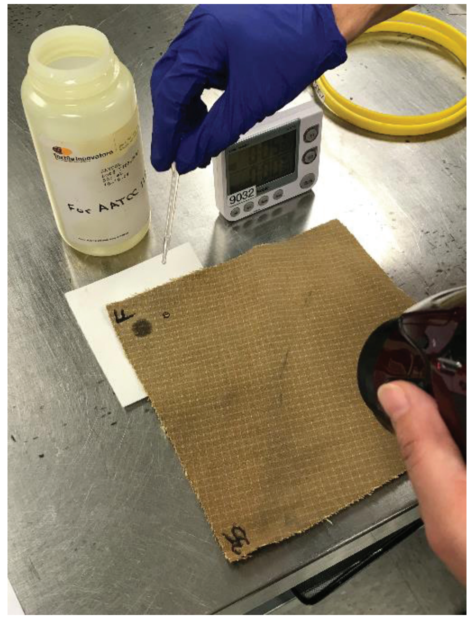


Figure 5: Measurement of vertical wicking distance

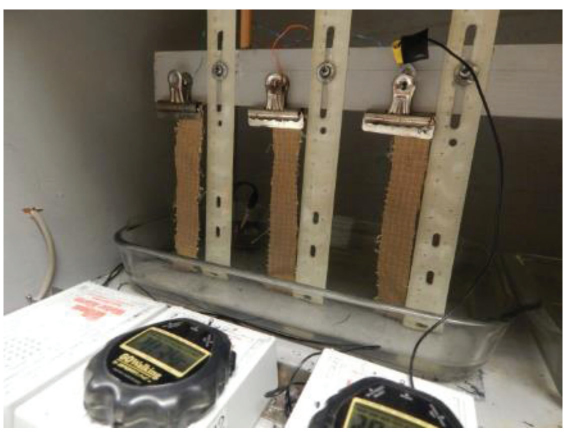


Figure 6: Measurement of horizontal wicking distance

Evaluation of Results and Discussion

General Physical Property Testing

Table 3 provides the results for the physical property testing of the outer shell and ballast fabrics.

Table 3: Results for Physical Property Testing of Candidate Outer Shell and Ballast Fabrics

Test Property	Test Method	Units	Fabric A*	Fabric B	Ballast Fabric
Unit area weight	ASTM D3776, Procedure C	oz/yd^2	7.8	6.0	10.5
Thickness	ASTM D1777	inch	0.021	0.017	0.028
Thread count	Microscopy	No./in.	48 (W) 47 (F)	44 (W) 47 (F)	39 (W) 23 (F)
Breaking strength (grab)	ASTM D5034	lb_f	256.8 (W) 279.5 (F)	319.7 (W) 310.3 (F)	461.7 (W) 374.4 (F)
Tear resistance (trapezoidal)	ASTM D5587	lb_f	86.2 (W) 91.4 (F)	157 (W) 152 (F)	68.5 (W) 56.6 (F)
Antimicrobial activity	AATCC 100	Log reduction	3	No reduction	3
Absorbency	AATCC 79	sec	> 60	> 60	> 60
Drying time	AATCC 199	min	Could not be measured	Could not be measured	Could not be measured

*Properties for Fabric A measured after 5 cycles of laundering per AATCC 135, (1, V, Ai).

These properties were primarily measured to characterize the general physical nature of the respective fabrics. The antimicrobial activity testing did show expected differences between treated and non-treated fabrics where the untreated or scoured Fabric B did not provide any reduction in the bacterial load on the fabric specimens. Neither the absorbency nor drying time tests provided useful measurements for discriminating fabric performance between treated and untreated fabrics. For the absorbency test, the water droplets simply did not fully wet the material, even for the untreated Fabric B. Drying time testing is tied to the absorbency test, and therefore could not be properly performed.

Liquid Property Testing

The more important findings came from evaluating each of the fabric samples for the different selected liquid absorption resistance and repellency properties. Test results for the outer shell fabric candidates, candidate ballast fabric, baseline cotton/polyester fabric, and each of the fabric samples removed from different outer shell materials in clothing or washed fabric are reported in Appendix A.

Some tests offered a variety of different measurements to choose from. For example, vertical wicking data were provided for 5, 10, 15, 20, 25, and 30 minute intervals, as well as the overall time to a 15 cm height. For purposes of comparing materials, the vertical wicking at 15 minutes was chosen. Similarly, horizontal wicking provided measurements of the wicking distance and wicking rate. The most discriminating measurements for this test were wicking distances for both length and width of the sample.

The results of this testing are graphically shown in Figures 7, 8, 9, and 10. A detailed review of these results yielded the following observations:

- *Water Absorption Resistance*. The baseline cotton/polyester fabric provided the highest amount of percent water absorption followed by the scoured Fabric B outer shell fabric. In contrast, the percent water absorption for the Fabric A outer shell fabric both before and after laundering was extremely low—both values were at 0.4%, well below the mandated requirement of <15% and more importantly, unchanged by 5 cycles of laundering. Data for the Lion Apparel samples, which included three different outer shell fabrics washed 40 times, did show significantly higher levels of water absorption. One used clothing sample did exceed the level of water absorption for the scoured Fabric B, while two others had similar values at around 18 to 19 percent. Most used clothing samples had water absorption levels between 2 and 12 percent.
- *Oil Repellency.* The large majority of samples showed poor repellency. With the exception of four different ISP or manufacturer provided clothing or fabric samples, all of the fabrics had a 0 rating for oil repellency, meaning that the sample failed to repel the oil liquid with the highest surface tension at 31.2 dynes/cm (in contrast, water has a surface tension of 72 dynes/cm). The exceptions included a coat that had been washed 10 times, a set of pants that had been washed 5 times (both 9 years old), a sample of Fabric A that had been washed 20 times at an ISP, and a retired set of pants that had an unknown number of launderings. The pristine Fabric A had a rating of 7 (out of 8), which was reduced to 6 following five laundering cycles. The scoured Fabric B, cotton/polyester, and Ballast Fabric samples all had zero oil repellency ratings.
- *Vertical Wicking.* As with water absorption resistance, the cotton/polyester baseline fabric had the highest levels of vertical wicking followed by the scoured Fabric B. One retired clothing sample constructed of Advance had similar vertical wicking values. Many but not all of the ISP or manufacturer provided samples had measurement levels of vertical wicking well below the cotton/polyester and scoured Fabric B samples. A few samples including the 20 time washed Fabric A and retired Fabric A–based coat from an ISP, had no measured vertical wicking. The pristine and washed Fabric A samples also showed no vertical wicking.
- *Horizontal Wicking.* The assessment of horizontal wicking provided a completely different discrimination of fabric performance. While horizontal wicking was greatest for the scoured Fabric B, the pristine Fabric A showed very little horizontal wicking. Of greatest interest was the fact that several samples, especially the different outer shell samples provided by Manufacturer #2 that were washed 40 times showed the highest levels of horizontal wicking, as did several samples from different ISPs that were greater than the measured horizontal wicking for the scoured Fabric B fabric. Some clothing samples had no measurement of horizontal wicking, which tended to be from newer, less washed clothing items.

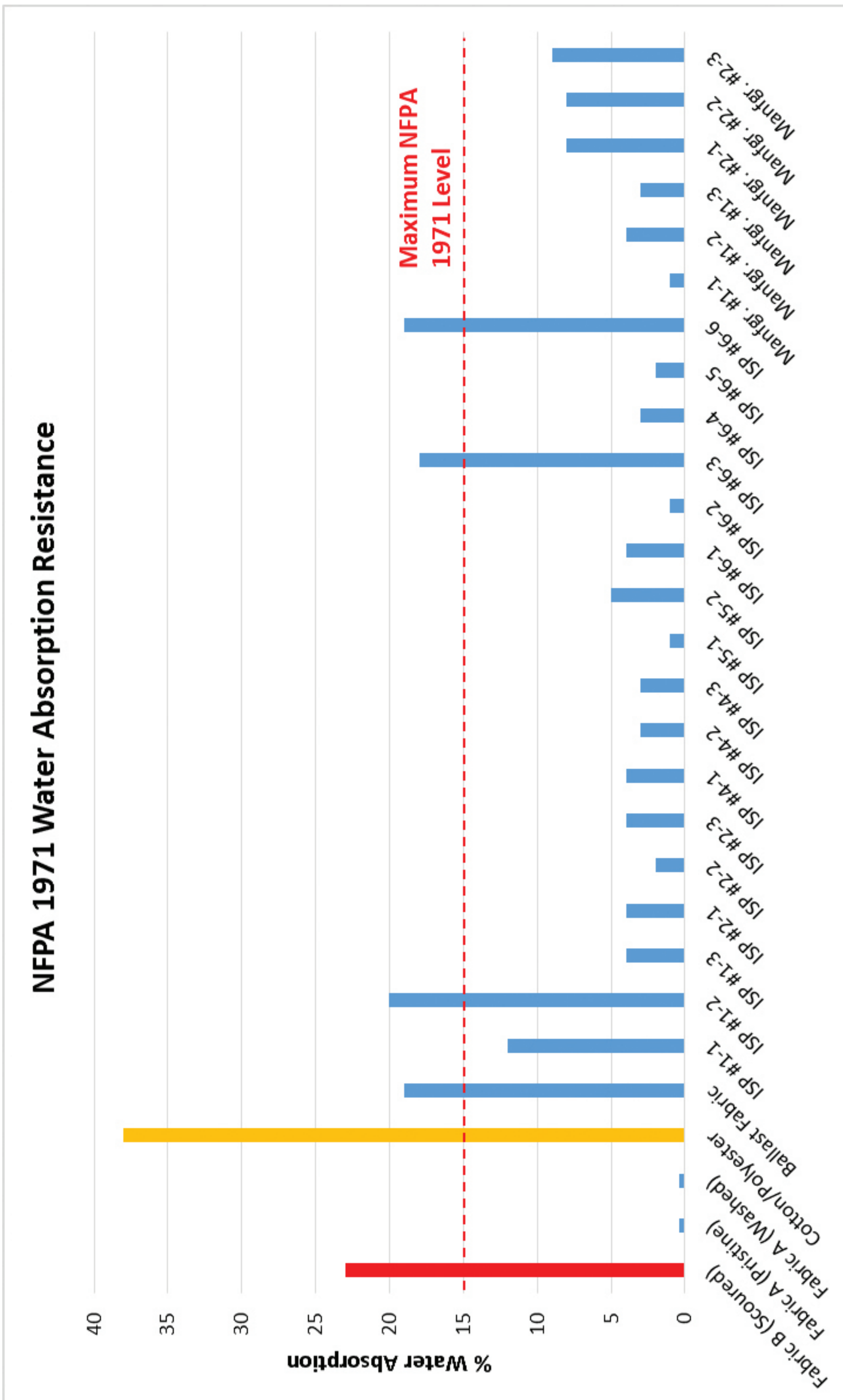
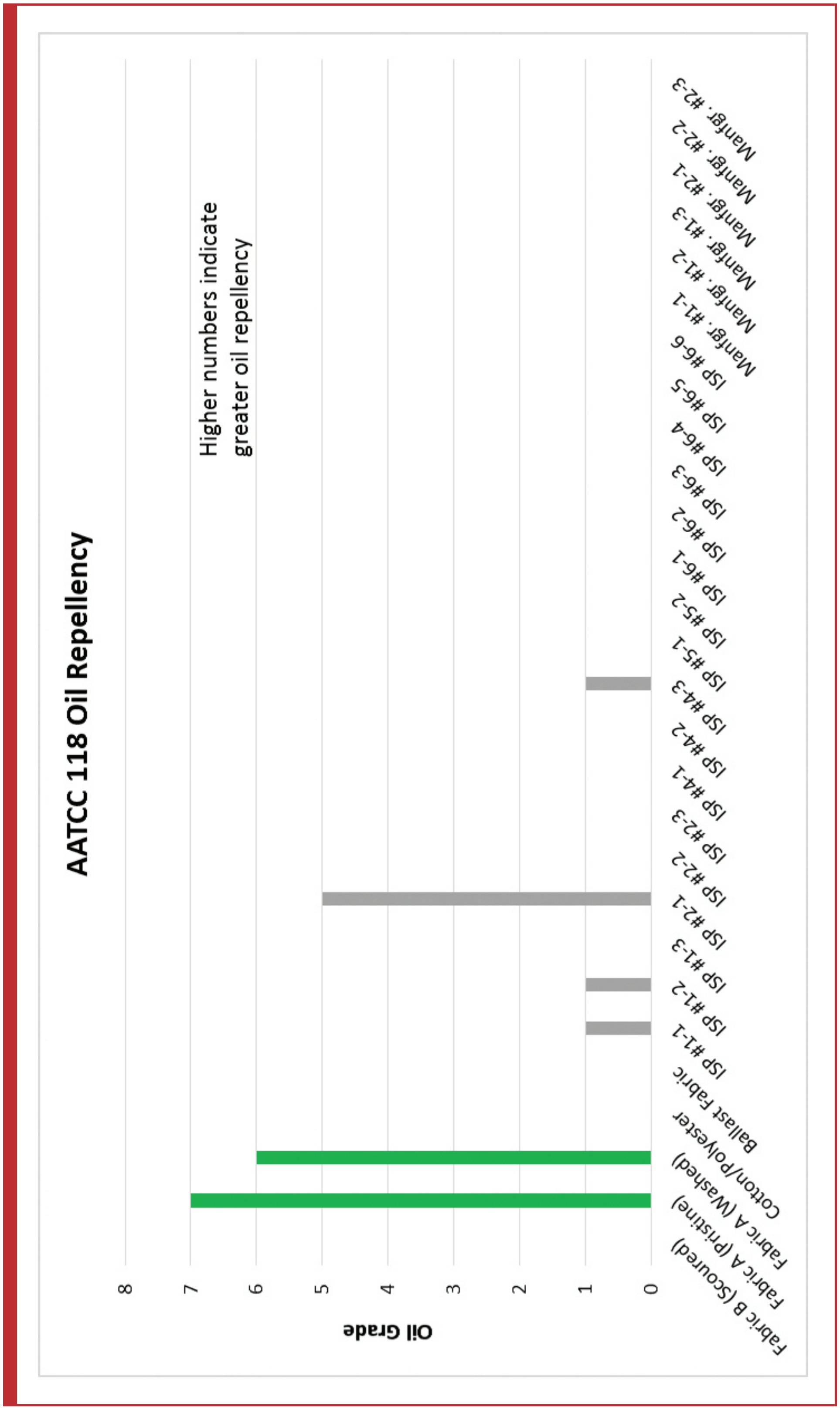


Figure 7: Water absorption resistance test results

Figure 8: Oil repellency test results



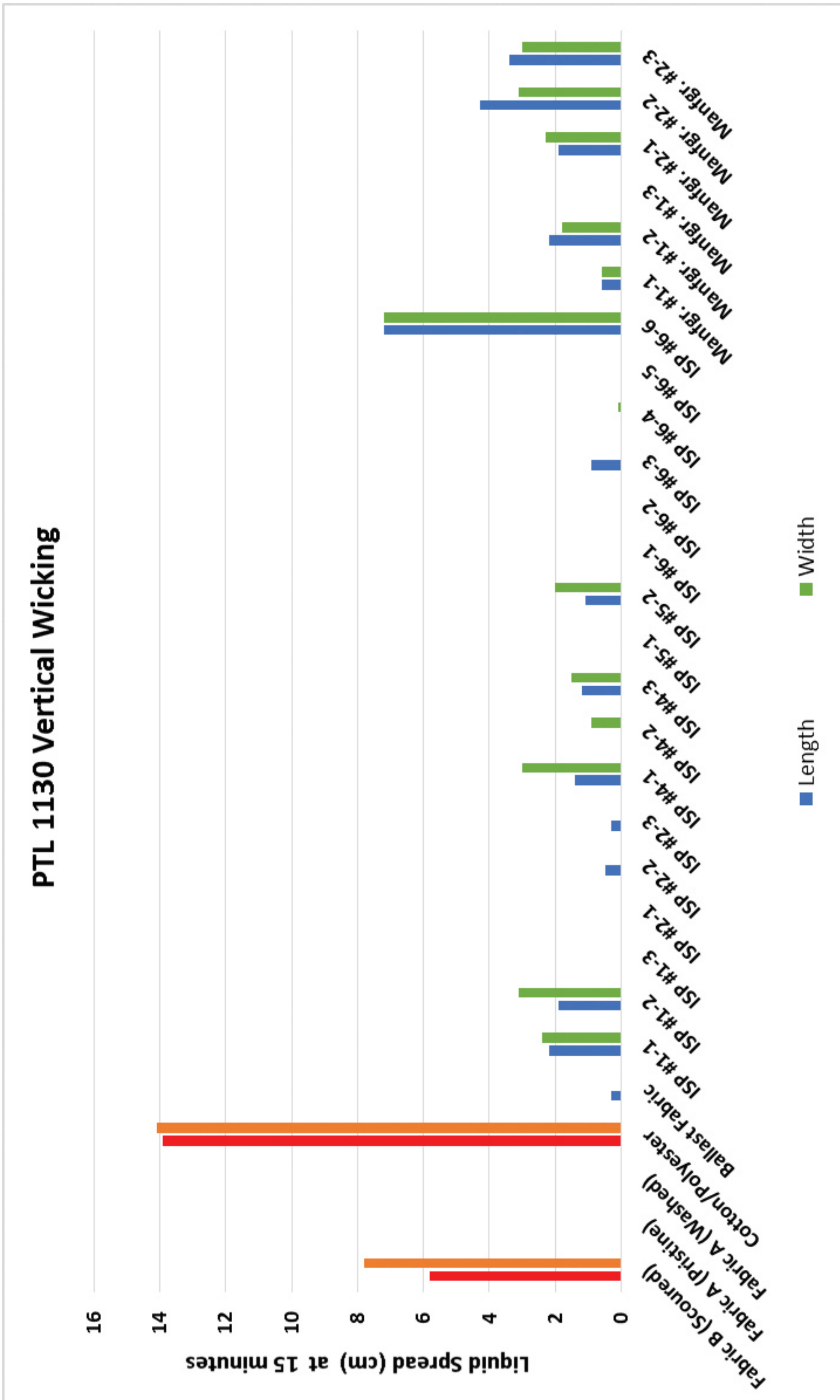


Figure 9: Vertical wicking test results

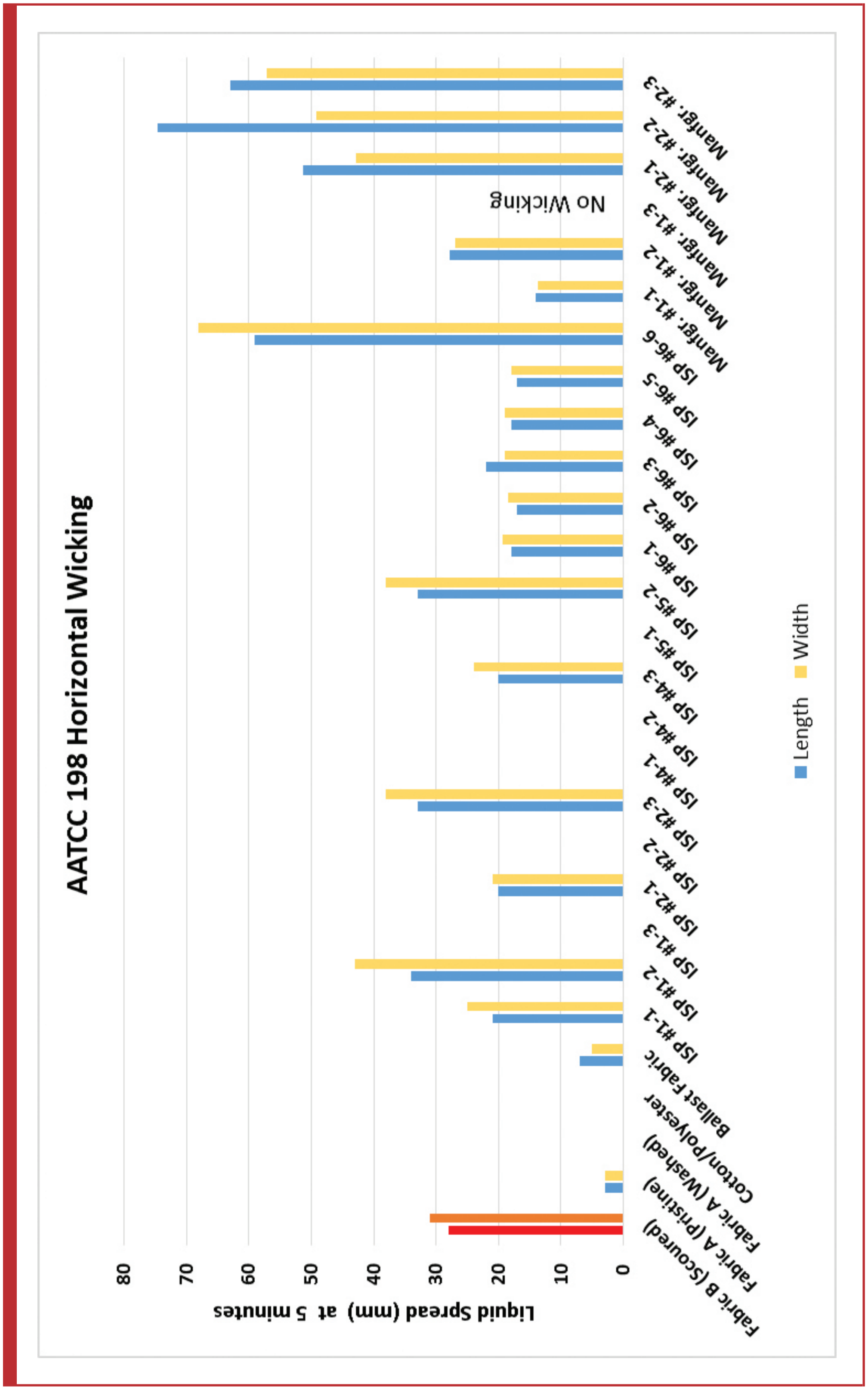


Figure 10: Horizontal wicking test results

A number of factors that could have partially explained the differences in liquid absorption and repellency characteristics that were not fully explored. For example, it was known that residual soiling will lower the fabric surface tension, allowing easier penetration of certain liquids, including water. In addition, the physical state of the individual fabrics provided by the ISPs and manufacturers was not known. Besides the liquid absorption, wicking, and repellency properties, only unit area weight was measured. Lastly, the investigation did not account for the specific differences in the various outer shell fabrics that were evaluated outside the two candidate fabrics used in the development of the cleaning verification procedures. It is highly likely that the combination of these factors would provide an impact on the ability of fabric to absorb or repel different liquids, as well as any observed wicking of those liquids in the fabric samples.

Conclusions

From this investigation, it was learned that the scoured Fabric B, while providing a material free of finishes and allowing easier absorption by different contaminant liquids, probably did not represent the types of outer shell materials and conditions of those materials that would be present for most used fire fighter protective clothing found in the field. While the water repellent–treated Fabric A possessed a high degree of resistance to both water absorption and vertical/horizontal wicking in addition to having high levels of oil repellency, some washing does reduce these properties to allow it to reflect the general liquid absorbency and repellency characteristics of clothing in the field. This information coupled with findings generated through the development of the cleaning verification procedures helped to validate the choice of Fabric A, when washed 10 times, to be a suitable surrogate outer shell for evaluating the effectiveness of cleaning processes. Information gained from this investigation also helped to establish the viability of the selected ballast fabric to be used as part of the cleaning verification procedures.

Appendix A: Liquid Absorption, Repellency, and Wicking Data for Selected Outer Shell and Other Selected Fabric Samples

Sample Designation	Type	Outer Shell	No. Cleanings	Oil Repellency AATCC 118 Grade (0–8)	Water Absorption NFPA 1971–2013 Section 8.25 (%)	Vertical Wicking PTL 1130 Length; Spread at 15 min (cm)
Fabric B (Scoured)	Material	Fabric B	None	0	23	5.8
Fabric A (Pristine)	Material	Fabric A	None	7	0.4	0
Fabric A (Washed)	Material	Fabric A	5	6	0.4	0
Cotton/Polyester	Material	Cotton/Polyester	10	0	38	13.9
Ballast Fabric	Material	Polyester	None	0	19	0.3
ISP #1-1	Coat	Fabric C	Unknown	0	12	2.2
ISP #1-2	Coat	Fabric C	Unknown	0	20	1.9
ISP #1-3	Pants	Fabric A	Unknown	0	4	0
ISP #2-1	Pants	Fabric D	4	0	4	0
ISP #2-2	Coat	Fabric E	3	0	2	0.5
ISP #2-3	Pants	Fabric D	5	0	4	0.3
ISP #4-1	Coat	Fabric D	10	1	4	1.4
ISP #4-2	Pants	Fabric C	5	1	3	0
ISP #4-3	Pants	Fabric F	11	0	3	1.2
ISP #5-1	Material	Fabric A	20	5	1	0
ISP #5-2	Material	Fabric E	20	0	5	1.1
ISP #6-1	Coat	Fabric I	Unknown	0	4	0
ISP #6-2	Coat	Fabric C	Unknown	0	1	0
ISP #6-3	Coat	Fabric J	Unknown	0	18	0.9
ISP #6-4	Pants	Fabric I	Unknown	0	3	0
ISP #6-5	Pants	Fabric J	Unknown	0	2	0
ISP #6-6	Pants	Fabric C	Unknown	0	19	7.2
Manfgr. #1-1	Pants	Fabric C	Unknown	1	1	0.6
Manfgr. #1-2	Pants	Fabric H	Unknown	0	4	2.2
Manfgr. #1-3	Pants	Fabric A	Unknown	0	3	0
Manfgr. #2-1	Coat/Pants	Fabric B	40	0	8	1.9
Manfgr. #2-2	Coat/Pants	Fabric E	40	0	8	4.3
Manfgr. #2-3	Coat/Pants	Fabric G	40	0	9	3.4

Sample Designation	Type	Outer Shell	No. Cleanings	Vertical Wicking PTL 1130 Width; Spread at 15 min (cm)	Vertical Wicking PTL 1130 Length; Time to 15 cm (min)
Fabric B (Scoured)	Material	Fabric B	None	7.8	>30
Fabric A (Pristine)	Material	Fabric A	None	0	>30
Fabric A (Washed)	Material	Fabric A	5	0	>30
Cotton/Polyester	Material	Cotton/Polyester	10	14.1	12.9
Ballast Fabric	Material	Polyester	None	0	>30
ISP #1–1	Coat	Fabric C	Unknown	2.4	>30
ISP #1–2	Coat	Fabric C	Unknown	3.1	>30
ISP #1–3	Pants	Fabric A	Unknown	0	>30
ISP #2–1	Pants	Fabric D	4	0	>30
ISP #2–2	Coat	Fabric E	3	0	>30
ISP #2–3	Pants	Fabric D	5	0	>30
ISP #4–1	Coat	Fabric D	10	3	>30
ISP #4–2	Pants	Fabric C	5	0.9	>30
ISP #4–3	Pants	Fabric F	11	1.5	>30
ISP #5–1	Material	Fabric A	20	0	>30
ISP #5–2	Material	Fabric E	20	2	>30
ISP #6–1	Coat	Fabric I	Unknown	0	>30
ISP #6–2	Coat	Fabric C	Unknown	0	>30
ISP #6–3	Coat	Fabric J	Unknown	0	>30
ISP #6–4	Pants	Fabric I	Unknown	0.1	>30
ISP #6–5	Pants	Fabric J	Unknown	0	>30
ISP #6–6	Pants	Fabric C	Unknown	7.2	>30
Manfgr. #1–1	Pants	Fabric C	Unknown	0.6	>30
Manfgr. #1–2	Pants	Fabric H	Unknown	1.8	>30
Manfgr. #1–3	Pants	Fabric A	Unknown	0	>30
Manfgr. #2–1	Coat/Pants	Fabric B	40	2.3	>30
Manfgr. #2–2	Coat/Pants	Fabric E	40	3.1	>30
Manfgr. #2–3	Coat/Pants	Fabric G	40	3	>30

Sample Designation	Type	Outer Shell	No. Cleanings	Vertical Wicking PTL 1130 Width; Time to 15 cm (min)	Horizontal Wicking AATCC 198 Length (mm)	Horizontal Wicking AATCC 198 Width (mm)
Fabric B (Scoured)	Material	Fabric B	None	>30	28	31
Fabric A (Pristine)	Material	Fabric A	None	>30	3	3
Fabric A (Washed)	Material	Fabric A	5	>30		
Cotton/Polyester	Material	Cotton/Polyester	10	11.9		
Ballast Fabric	Material	Polyester	None	>30	7	5
ISP #1–1	Coat	Fabric C	Unknown	>30	21	25
ISP #1–2	Coat	Fabric C	Unknown	>30	34	43
ISP #1–3	Pants	Fabric A	Unknown	>30	No wicking	
ISP #2–1	Pants	Fabric D	4	>30	42	48
ISP #2–2	Coat	Fabric E	3	>30	19	17
ISP #2–3	Pants	Fabric D	5	>30	20	21
ISP #4–1	Coat	Fabric D	10	>30	No wicking	
ISP #4–2	Pants	Fabric C	5	>30	No wicking	
ISP #4–3	Pants	Fabric F	11	>30	20	24
ISP #5–1	Material	Fabric A	20	>30	No wicking	
ISP #5–2	Material	Fabric E	20	>30	33	38
ISP #6–1	Coat	Fabric I	Unknown	>30	18	19.4
ISP #6–2	Coat	Fabric C	Unknown	>30	17	18.4
ISP #6–3	Coat	Fabric J	Unknown	>30	22	19
ISP #6–4	Pants	Fabric I	Unknown	>30	18	19
ISP #6–5	Pants	Fabric J	Unknown	>30	17	18
ISP #6–6	Pants	Fabric C	Unknown	>30	59	68
Manfgr. #1–1	Pants	Fabric C	Unknown	>30	14	13.7
Manfgr. #1–2	Pants	Fabric H	Unknown	>30	27.8	27
Manfgr. #1–3	Pants	Fabric A	Unknown	>30	No wicking	
Manfgr. #2–1	Coat/Pants	Fabric B	40	>30	51.3	42.8
Manfgr. #2–2	Coat/Pants	Fabric E	40	>30	74.6	49.2
Manfgr. #2–3	Coat/Pants	Fabric G	40	>30	63	57.2

Sample Designation	Type	Outer Shell	No. Cleanings	Horizontal Wicking AATCC 198 Time (sec)	Horizontal Wicking AATCC 198 Rate (mm^2/sec)
Fabric B (Scoured)	Material	Fabric B	None	300	2.3
Fabric A (Pristine)	Material	Fabric A	None	300	0.2
Fabric A (Washed)	Material	Fabric A	5		
Cotton/Polyester	Material	Cotton/Polyester	10		
Ballast Fabric	Material	Polyester	None	300	0.1
ISP #1–1	Coat	Fabric C	Unknown	300	1.3
ISP #1–2	Coat	Fabric C	Unknown	300	4
ISP #1–3	Pants	Fabric A	Unknown		
ISP #2–1	Pants	Fabric D	4	300	5.3
ISP #2–2	Coat	Fabric E	3	300	0.9
ISP #2–3	Pants	Fabric D	5	300	1.1
ISP #4–1	Coat	Fabric D	10		
ISP #4–2	Pants	Fabric C	5		
ISP #4–3	Pants	Fabric F	11	300	1.3
ISP #5–1	Material	Fabric A	20		
ISP #5–2	Material	Fabric E	20	300	3.3
ISP #6–1	Coat	Fabric I	Unknown	300	0.9
ISP #6–2	Coat	Fabric C	Unknown	300	0.8
ISP #6–3	Coat	Fabric J	Unknown	400	1.1
ISP #6–4	Pants	Fabric I	Unknown	300	0.9
ISP #6–5	Pants	Fabric J	Unknown	300	0.8
ISP #6–6	Pants	Fabric C	Unknown	280	15.1
Manfgr. #1–1	Pants	Fabric C	Unknown	300	0.5
Manfgr. #1–2	Pants	Fabric H	Unknown	300	2
Manfgr. #1–3	Pants	Fabric A	Unknown		
Manfgr. #2–1	Coat/Pants	Fabric B	40	300	5.7
Manfgr. #2–2	Coat/Pants	Fabric E	40	300	11.6
Manfgr. #2–3	Coat/Pants	Fabric G	40	300	9.4

Appendix B: Fabric Key

Fabric	Weight (osy)	General Composition	Weave
A	7.5	55% para-aramid, 37% PBI, 8% liquid crystal polymer, multi-filament	Ripstop
B	6.6	60% para-aramid, 40% meta-aramid	Twill
C	7.2	60% para-aramid, 40% meta-aramid	Ripstop
D	7.25	60% para-aramid, 40% PBI	Plain
E	7.0	65% para-aramid, 35% PBI, multi-filament	Twill
F	7.0	60% para-aramid, 40% meta-aramid	Twill
G	7.0	75% para-aramid, 25% meta-aramid	Twill
H	7.5	60% para-aramid, 40% PBI	Ripstop
I	7.5	60% para-aramid, 40% PBI	Ripstop
J	7.5	93% meta-aramid, 5% para-aramid, 2% anti-static	Plain