Evaluation of the Cleaning Effectiveness and Impact of Esporta and Industrial Cleaning Techniques On Firefighter Protective Clothing

Technical Report

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EXECUTIVE SUMMARY

A study was undertaken to compare two different laundering processes in terms of soiling removal, chemical contaminant removal, and effects on key firefighter protective clothing properties. The first process (“Esporta”) represents a unique machine and chemical approach, which is designed to provide large throughput but in a manner where potential damage to the clothing is minimized while providing a comprehensive cleaning process. The second process (“conventional”) was representative of a generic industrial laundering method and in fact was based on the garment conditioned specified in NFPA 1971, which set the minimum performance requirements for firefighter protective clothing. To carry out the study, two different fabric systems were chosen for evaluation that represented a range of fabric use by the fire service.

For soiling removal, a synthetic soil was applied to outer shell fabrics using a Launder-Ometer based process using techniques established by the American Association of Textile Chemists and Colorists (AATCC). Three different methods were used for comparing soiling removal that included visual comparisons, the application of AATCC Gray Scale color and staining ratings, and spectrophotometric measurements of color and color changes. Based on each assessment method, significant differences were noted for improved soiling removal by the Esporta laundering method; however, neither method was able to remove all soiling. The method of soiling fabrics was found to relatively aggressive.

Chemical decontamination efficiencies were assessed using a modified approach originally described in the U.S. Fire Administration report, “Research, Testing and Analysis on the Decontamination of Firefighting Protective Clothing and Equipment,” USFA Contract No. EME-96-CO-0505 (February 1999). In this testing, outer shell fabrics were contaminated with ethyl benzene, anthracene, and dioctyl phthalate as representative fireground chemicals, and then subjected to one cycle of cleaning by each laundering process. The fabric specimens were then analyzed to determine the remaining levels of chemical contaminants. Based on this testing approach, the Esporta laundering process showed higher decontamination efficiencies compared to the conventional process, though both processes showed 100% removal of ethyl benzene.

The appendix procedures provided in NFPA 1851, *Standard on Selection, Care, and Maintenance of Protective Clothing* (2001 edition) were used to assess the impact of each laundering process on key protective clothing properties. While a range of laundering process impacts were observed from both the Esporta and conventional laundering processes, in general the Esporta laundering process showed less reductions of protective performance as compared to the conventional laundering process. These findings were observed specifically for outer shell breaking strength, seam strength, liquid penetration resistance, viral (bloodborne pathogen) penetration resistance, and trim nighttime visibility performance. As expected, the effects on flame resistance were negligible in nearly all cases. Tear resistance results were mixed. Similar to other research, thermal protective performance improved for both processes. The only performance area where the conventional laundering process had less impact on clothing properties was for water absorption resistance. This result is not entirely unexpected because the better soiling and contaminant removal efficiencies for the Esporta laundering process would also have an impact on removing fabric repellent finishes. Another examination of the Esporta laundering process could be made with the reapplication of repellent finishes.

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ACKNOWLEDGEMENT

A substantial portion of the study work was conducted by the Department of Human Ecology at the University of Alberta under the direction of Dr. Elizabeth Crown. The University of Alberta provided input to the development of test methods, conducted the soiling and chemical contaminant removal tests, and performed the majority of clothing performance tests. The University of Alberta also conducted statistical analyses for many of the data provided in this report.

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INTRODUCTION

This study was designed to examine differences in the effectiveness of two different processes for cleaning firefighter protective clothing. One process involved the use of the Esporta washing machine and chemical system. The Esporta washing machine utilizes a plastic insert design that ensures that the items being cleaned are held securely in place while going through the wash and dry cycle. The Esporta machine was used in combination with a four stage ZEP – Esporta Wash System of chemicals. The chemicals include a detergent, penetrator detergent, force additive, and fragrance. The second process was based on a standard industrial washing technique specified as a preconditioning method prior to fabric testing in NFPA 1971, Standard on Protective Ensembles for Structural Fire Fighting (2000 Edition). Testing under controlled conditions was used to evaluate cleaning effectiveness in terms of soiling removal and chemical decontamination and as well as the effects of repeated laundering with each process on selected firefighter protective clothing materials. The approach used to conduct these evaluations was based partly on information provided in the appendix of NFPA 1851, *Standard on Selection, Care, and Maintenance of Structural Fire Fighting Protective Ensembles* (2001 Edition). Other procedures were devised based on prior work conducted by the U.S. Fire Administration in "Research, Testing and Analysis on the Decontamination of Firefighting Protective Clothing and Equipment," USFA Contract No. EME-96-CO-0505 (February 1999). The study was designed to provide an objective and quantitative comparison between the two laundering processes and assist in establishing future procedures for evaluating the impact of prospective laundering processes on firefighter protective clothing. A substantial portion of the study work was conducted by the Department of Human Ecology at the University of Alberta under the direction of Dr. Elizabeth Crown.

BACKGROUND

In normal everyday use, any clothing becomes dirty absorbing sweat from the wearer and soils from the outside environment. General cleaning of clothing, involving chemical (detergent) and physical processes (high temperature water and agitation), removes these substances from the clothing or equipment materials. Clothing and equipment can also become contaminated with other substances, principally chemicals, particulates, blood, and other body fluids. The removal of these substances is most often referred to as decontamination. In the activity of structural fire fighting, both cleaning and decontamination of protective clothing and equipment are needed on a frequent basis. It is also important to recognize that fire fighting protective clothing entails three principal layers, which provide specific protective functions and that these individual layers are affected by contamination and cleaning differently.

Types of Contamination

Chemicals. Firefighters respond to a variety of incidents each presenting its own unique hazards. Traditionally, most fire fighting activity has centered on structural fires. The combustion of wood releases several combustion products into the atmosphere, principally carbon monoxide and other simple hydrocarbons. Structural fires have changed over the past several years because building materials have changed.[1] Roofing, insulation, carpets, paints and other construction materials all contribute to an ever growing diversity of chemical products founds at fires. The increased use of plastics and other synthetic materials release different kinds of combustion products, many of them highly toxic or carcinogenic.[2-4] Examples of fire combustion products include:

- Carbon monoxide and carbon dioxide;
- Inorganic gases (hydrogen sulfide, hydrogen cyanide, nitrogen oxides)
- Acid gases (hydrochloric acid, sulfuric acid, nitric acid);
- Organic acids (formic acid, acetic acid);
- Aldehydes;
- Chlorinated compounds (carbon tetrachloride and vinyl chloride);
- Hydrocarbons (benzene);
- Polynuclear aromatic compounds (PANs); and
- Metals (cadmium, chromium).

In addition, chemicals located at the site of a fire further contribute to hazardous contaminants in fire smoke. A classic example are polychlorinated biphenyls (PCBs), found in electrical transformers and other equipment, which when burned may form dioxin, an acutely deadly substance. Even the normal household will contain cleaning supplies, pesticides, pool chlorine and other substances that contribute to release of toxic substances at fires.

Contact of these chemicals with fire fighting clothing can both penetrate and permeate protective fabrics. Since most firefighter protective clothing uses porous fabrics, the chemical vapors or liquids simply ***penetrate*** or pass through the pores of the material. Molecules of chemicals can also ***permeate*** into the fibers or coatings of clothing materials and can remain in the material for long periods of time, depending on the types of exposure chemical(s) and care given to the clothing. Chemicals that get into the clothing from either means can directly contact the wearer's skin.

Particulates. In addition to liquid or vapor chemical contaminants, a tremendous amount of ash, soot, and other solid matter are released during fires and fire fighting activities. This solid matter provides the visible portion of smoke and is the primary cause of residue left on structures and clothing following fires. Soot and ash represent incomplete products of combustion; that is, unburned fuel or agglomerated solids that fail to completely burn during the fire. During combustion, synthetic materials create an increase in the amount of particulate matter, hence the "black" smoke from burning plastics. Since soot particles are very porous, they tend to adsorb other hazardous chemicals on their surfaces. Ash, resins, and other particles from fire smoke can easily become entrapped within the fibers of clothing. Accumulation of soot on protective clothing becomes visible as soiled or "dirty" areas. In some cases, these "soils" are made of melted resins or plastics which, in the heat of the fire, become liquid and spread even further throughout the protective clothing.[5] In other cases, many of the particles are too small to see (less than 10 microns in diameter) and can easily penetrate into the inner layers of clothing such as liner and barrier materials contacting the wearer's skin.[6]

Chemical dusts, lead particles, and asbestos may also be encountered at fires and other responses. For example, though asbestos is principally an inhalation hazard, asbestos can cling to the protective clothing and be released when the responder is not wearing his or her SCBA.[7-8] Similarly, lead and other toxic dusts can fill clothing pores and contaminate the firefighter's skin after the incident.

Biological Agents. A relatively new concern in emergency response has been the potential exposure to blood or other body fluids containing pathogens, particularly the Human Immunodeficiency Virus (HIV) or AIDS virus, and Hepatitis B and C viruses. These viruses are extremely small in size and are transmitted by blood or other biological fluids. The risk is high since emergency patient care is major function of many fire departments. The extrication of victims from automobile accidents and rescue of injured persons from fires and other incidents all involve the potential for this exposure. Even minute droplets of blood are capable of carrying thousands of virus.[9]

As with chemicals, most protective clothing materials readily absorb blood. The effectiveness of clothing in preventing blood contact with the skin depends on the type of clothing and materials used in its construction. Protective clothing can readily be contaminated with blood not only on the surface but on inner layers as well. Portions of the turnout coats such as the wristlets and the collar are particularly susceptible to this contamination because there are no barrier materials behind their knit material construction. Even though the skin itself is a barrier to blood penetration, skin scratches and abrasions common during the rough physical environments of emergency response increase the risk for infection.[10]

Hazards of Contaminated Protective Clothing

When protective clothing becomes laden with particles, the clothing's performance is diminished in several ways:

1. ***Soiled turnout clothing reflects less radiant heat.*** After materials are saturated with hydrocarbons, these materials will tend to absorb rather than reflect the radiant heat from the surrounding fire providing less thermal insulation for the firefighter.

2. ***Turnout clothing materials which are heavily contaminated with hydrocarbons are more likely to conduct electricity***, increasing the danger to the firefighter entering a building or vehicle where wiring may still be live.

3. ***Turnout clothing materials which are impregnated with oil, grease and hydrocarbon deposits from soot and smoke, can ignite*** and cause severe burns and injuries, even if the materials are normally flame resistant.

Even with the advent of specialized hazardous materials response teams within major fire departments, various chemicals can be encountered in normal fire fighting activities. Additionally, exposure to oils, gasoline, and lubricants may occur around fire station vehicles. During responses, exposures to liquids ranging from pesticides to acids to chemical solvents may occur either knowingly or unknowingly. These exposures, in addition to being hazardous, can also degrade protective clothing material. For example:

- Clothing fabrics may become weakened and tear more easily;
- Thread or seam sealing tape may become loose;
- Water repellency treatments may be removed;
- Reflective trim can become less visible;
- Helmet shells/faceshield or SCBA masks visors may pit or craze; and
- Clothing or equipment hardware may be corroded.

Principles of Laundering Techniques and Factors Affecting Their Selection

The basic principle for cleaning materials is to break down the bonds between the chemical and the fabric molecules. In some cases, physical actions such as the pressure caused by passing water through the material, or physical scrubbing can remove some soils. Chemical agents, such as detergents, break down the chemical bonds which hold soils and stains to the clothing fabrics, hold these soils in suspension, and then release the soils through rinsing action. A variety of cleansing agents, machines, wash temperatures, and drying conditions are used in clothing cleaning and decontamination. There is a large range of attributes for the number of processes that can be used for cleaning fire fighting protective clothing. NFPA 1851 sets some boundaries for these attributes for such factors as wash temperature ($\leq 105^{o}$F), wash chemistry ($6.0 \leq pH \leq 10.5$; no chlorinated bleach), and drying process (air drying or tumble drying with no or low heat). The committee responsible for NFPA 1851 is further considering setting a maximum acceleration on machine extract speeds at 100 G's.

Several factors are involved in evaluating the effectiveness and usefulness of laundering methods for cleaning and decontaminating firefighter protective clothing. Among these are:

- The ability to remove different types of fireground soils and stain;
- The efficiency of the method in removing specific contaminants;
- The type of contaminants removed by the method;
- The machine's capacity and throughput for multiple sets of protective clothing;
- The machine's ability to be programmed with different wash formulations and use different chemicals;
- The ease of using the process for cleaning and/or decontamination;
- The amount of time required for the process (on the basis of per set of gear);
- The amount of effluent and available methods of handling wastewater ;
- The effect of the cleaning and decontamination process on the clothing or equipment;
- The costs associated with the cleaning and decontamination process versus alternative methods of handling; and
- The availability of the process.

Fire departments and other organizations must choose a process that best fits their needs. A number of departments are turning towards independent service providers for cleaning and repair. Other departments have implemented centralized locations for cleaning of firefighter protective clothing.

Effects of Laundering Processes on Clothing

While various cleaning methods remove soils and may remove contamination, they can also damage clothing materials over time. In essence, both wear and cleaning processes damage clothing over time.[10] Some common cleaning agents, such as sodium hypochlorite bleach and other chlorine-containing bleaches, can actually rapidly destroy clothing through deterioration of para-aramid-based materials and thread. Although dry cleaning would seem to provide a good means of removing tough stains and many contaminants, most dry cleaning chemicals damage certain components of firefighter protective clothing. Some detergents and specialized cleaning products, particularly those used in large scale industrial laundering processes, may also cause some degradation of clothing properties. Over the years, a number of cleaning restrictions have been found to apply to firefighter protective clothing, owing to its complex design and high technology materials. In addition to the damaging effects of bleach and high/low pH chemicals, some examples include:

- Failure to separate outer shells and liners can cause redeposition of soils on liners from shells and cause damage to liners.
- High wash temperatures can cause excessive or uneven shrinkage of fabrics.
- High machine drying conditions cause similar damage and create additional wear on clothing and clothing materials and components.
- Agitator top loading washing machines create more wear on protective clothing.
- High machine acceleration during extraction can loosen seams and damage moisture barriers and the machines attempt to force wash water through relatively impervious layers of the clothing.

These effects become more pronounced as the number of cleanings on a single item increases. This degradation may be either chemical or physical in nature.

The protective qualities of structural fire fighting protective clothing depend on the combined characteristics of several materials and components. Individual layers of firefighter clothing have separate functions for flame resistance, water penetration resistance, and insulation, and collectively provide thermal protection to the wearer. These layers may be preferentially affected by decontamination processes. For example, one decontamination practice may effectively remove contaminant from the outer shell but degrade the moisture barrier in the process.

APPROACH

Objectives

The objective of this study was to evaluate and compare the Esporta machine and wash system chemicals against standard industrial laundering procedures used for cleaning fire fighting protective garments (pants and coats). Evaluations and comparison were made in three different areas:

1. Ability to remove soiling from outer shell fabrics

2. Ability to remove semi-volatile chemical contaminants common to fireground environments from outer shell fabrics
3. Impact of the laundering procedures on key protective clothing performance properties for specific clothing layers and components

To meet these objectives, a comprehensive test plan was prepared.

General Test Plan

The evaluation of laundering processes encompasses a variety of testing methods that measure the effectiveness of cleaning process to remove soiling, chemical contamination, and biological contamination. For this study, evaluations were made for removal of soiling and chemical contamination. Removal of biological contamination was not considered for this study since the location of the laundering processes was not in proximity to laboratories with capabilities of analyzing microbiological contamination, which require rapid assessment. Since standardized procedures have not been established for these evaluations, special techniques were developed, which were in part based on earlier work described in the U.S. Fire Administration Study "Research, Testing and Analysis on the Decontamination of Firefighting Protective Clothing and Equipment," USFA Contract No. EME-96-CO-0505 (February 1999). An overview of the evaluation approaches for cleaning efficacy against both soiling and chemical contaminants is provided in Table 1.

Table 1 – Methods for Evaluating the Cleaning Effectiveness of Cleaning Service Contractor Procedures

Type of Evaluation	Types of Clothing Samples	Method of Contamination	Method of Assessment
Removal of soiling	Outer shell materials including Nomex IIIA and PBI/Kevlar	Soiling per modified procedures from AATCC 123, *Carpet Soiling: Accelerating Soiling Method*	Unsoiled and soiled materials will be assessed visually, against the AATCC gray scale for determining shade changes, and using spectrophotometer measurements.
Removal of chemical contamination	Outer shell materials including Nomex IIIA and PBI/Kevlar	Specimens were immersed in a solvent, containing specific concentrations of ethyl benzene, anthracene, and dioctyl phthalate and allowed to dry. A portion of the specimens were used to measure contaminant levels while another portion of samples is subjected to the selected laundering process.	The samples are extracted using diethyl ether and aliquots of the extract are analyzed by gas chromatograph/ mass spectrometry. Decontamination efficiency is determined by comparing pre-wash and after wash levels of contaminants.

The impact of the laundering processes on key protective clothing performance properties was also evaluated. The general approach used for this evaluation was based on procedures provided in the appendix of NFPA 1851, *Standard on Selection, Care, and Maintenance of Structural Fire Fighting Protective Ensembles* (2001 Edition).

Laundering Processes Evaluated

Two different laundering processes were evaluated. Both processes are considered processes that would represent industrial washing approaches; however, these laundering processes could also be implemented at a relatively small independent service provider or within the centralized location for a fire department. Specific details on both the types of machines, chemicals, and process formulations are provided in the sections below. The two processes are referred to as "Esporta" (machine, chemicals, and formulation) and "conventional" (machine, chemicals, and formulation).

Washing Machines. For the Esporta process, an Esporta ES3250 washer-dryer was used for this testing, in the washer mode only. The Esporta ES3250 is a fully programmable machine using a touch screen microprocessor control system that allows either full operator control or one touch start with preprogrammed formulations. The key feature of the Esporta ES3250 and other Esporta washing machines is the use of plastic cage inserts within the stainless steel drum that segregates items for washing to minimize clothing agitation and lessen damage. In the conventional process, a 40-pound capacity Wascomat "Dual-Use" SU 140 G-Force Wetcleaner (Model # SU640CA) was used for washing. Key characteristics for each machine are provided in Table 2 below.

Table 2 – Comparison of Washing Machines Used in Study

Characteristic	**Esporta ES3250**	**Wascomat SU640CA**
Machine size (W x D x H)	80½" x 51" x 77 ½"	29½" x 36" x 52¼"
Wash capacity	360 lbs	40 lbs
Wash/rinse speed	Variable (programmable)	44 rpm
Extract speed	118 rpm	619 rpm (140 Gs)
Type of controller	Microprocessor	Microprocessor
Formulation capacity	99 wash formulations	192 wash formulations

Photographs of both machines are provided in Figures 1 and 2. Equipment specifications by the manufacturers are provided in Appendix A.

Chemical Systems. Four different chemicals used in 4 stages were used as part of the Esporta process. These included:

- Stage 1 – Tak 1 Detergent – enzyme-based detergent with surfactants used to breakdown biological contaminants and basic soils with pH of 9.5.

Figure 1 – Esporta ES3250 Machine

Figure 2 – Wascomat SU640CA Machine

- Stage 2 – Penetrator Detergent – contains synergistic blend of detergents, detergent builders, water-soluble solvents and optical brighteners to break down oil-based soils with buffered pH of 9.5.

- Stage 3 – Force Additive – Blend of peroxyacetic acid and hydrogen peroxide to neutralize residual alkalinity and the kill remaining biological contaminants on contact.

- Stage 4 - Fragrance

The 1993 AATCC Standard Reference Detergent was used for the conventional laundering process. This detergent is produced the American Association of Textile Chemists and Colorists for the evaluation of laundry-based properties of clothing and fabrics. This detergent is specified in the conditioning of whole garments as part of the test procedures in NFPA 1971, *Standard on Protective Ensembles for Structural Fire Fighting* (2000 Edition). No other chemicals were used in the conventional laundering process.

Wash Formulations. The wash formulation used in the Esporta laundering process is shown in Table 3 below. This formulation consists of a 24-step process with an approximate run time of 2 hours. In comparison, the wash formulation specified in NFPA 1971 for whole garment conditioning was used. This latter process consists of an 11-step process that has a run time of approximately 31 minutes. However, the number of steps is not a direct comparison since the Esporta wash formulation includes extra details that are combined steps for the conventional wash formulation (e.g., the addition of each chemical is shown as an individual step in the Esporta wash formulation whereas these steps are combined for the conventional wash formulation).

Drying Procedures. For the purposes of this study, drying was done uniformly on all samples by hanging and allowing ambient air drying. This approach was used because the principal comparison was to be with washing processes and drying practices vary with the location. Furthermore, the U.S. Fire Administration found significant differences in the impact of drying procedures on contaminant removal.

Comparison between Laundering Processes. Some of the key differences between the laundering processes and wash formulations are:

- The Esporta machine is significantly larger (having a capacity that is roughly 9 times larger) and thus requires more time for filling with water, draining, and extracting.

- The Esporta wash formulation includes a pre-flush step (water only) that is not part of the conventional wash formulation.

- The Esporta wash formulation uses two separate chemical steps – an initial step where the first two chemicals are added, and a second step where the third chemical is added. In comparison, the conventional wash formulation uses a single chemical and has a carry over for residual detergent. Overall the Esporta laundering process uses a total of 4 chemicals.

Table 3 – Esporta and Conventional Wash Formulations

Esporta Wash Formulation				Conventional Wash Formulation			
Operation	**Time (min.)**	**Temp. (°F/°C)**	**Water Level**	**Operation**	**Time (min.)**	**Temp. (°F/°C)**	**Water Level**
Rotation at 16 rpm	---			Suds	10	120/49	Low
Water in	8	103/40	High	Detergent (45 g)	*		
Run – flush bath	5			Drain	1		
Drain	2			Carry-over	5	120/49	Low
Water in	8	103/40	High	Drain	1		
Chemical #1	1.5*			Rinse	2	100/38	High
Chemical #2	1.5*			Drain	1		
Run – wash bath	10			Rinse	2	100/38	High
Drain	2			Drain	1		
Water in	8	85/30	High	Rinse	2	100/38	High
Chemical #3	1.6*			Extract **	5		
Run – wash bath	10						
Drain	2						
Extract – 60 rpm	2						
Water in	8	85/30	High				
Run – rinse	6						
Drain	2						
Extract – 60 rpm	2						
Water in	8	85/30	High				
Chemical #4	1*						
Run – rinse	6						
Drain	2						
Extract – 60 rpm	2						
Extract – 150 rpm	7						

* Chemical or detergent addition occurs during water in or suds step, respectively
** Extract specific to machine (for conventional process with Wascomat SU640CA, extract occurs at 619 rpm.

- The conventional wash formulation uses three rinses compared to the two rinses that are part of the Esporta wash formulation.

- The Esporta wash formulation includes an extraction step following the last wash bath and each rinse.

- The Esporta wash formulation uses a significantly lower extraction speed compared to the conventional wash formulation (60 to 150 rpm versus 619 rpm).

Selection and Preparation of Samples

Material Selection. For the purposes of limiting materials to a manageable set of samples, two sets of firefighter protective clothing materials were chosen that included 2 outer shells, 2 moisture barriers, and 2 thermal barriers, in addition to three trim materials, commonly used by the fire service. These materials were grouped into two primary composites for evaluation:

1. ***System 1:*** 7.5 oz Nomex outer shell (Southern Mills Defender 750 Plainweave, Shelltite finish), ePTFE-based, Vilene substrate moisture barrier (W. L. Gore RT7100 Type 3A), Kevlar batt with Nomex face cloth thermal barrier (Southern Mills Aralite) with Reflexite Power Trim.

2. ***System 2:*** 7.5 oz PBI/Kevlar outer shell (Southern Mills Kombat 750 Shelltite finish), ePTFE-based moisture barrier (W. L. Gore & Associates Crosstech PJC 2C), 3 layers of 1.5 oz E89 spunlace Nomex quilted to a 3.4 oz spun woven Nomex face cloth thermal barrier (Southern Mills 3-layer E89).

Trim materials evaluated include Reflexite Power Trim, 3M, Scotchlite Trim (fluorescent yellow), and 3M Scotchlite Triple Trim.

General Sample Assembly and Preparation. For the evaluation of cleaning effectiveness, samples were prepared from outer shell fabrics that have already been subjected to 5 cycles of laundering and drying per AATCC 135, Machine Cycle 1, Wash Temperature V, and Drying Procedure Ai. This is a common preconditioning technique specified in NFPA 1971 that is used to simulate accelerated washing and partially remove certain repellent finishes that limit contamination of clothing materials. These samples were then soiled or contaminated using selected contaminants and procedures described in later sections. Following the simulation of contamination, the sample fabrics are then subjected to the cleaning process and then assessed for the removal of the specific contaminants.

Additional samples were prepared for evaluating effects of both laundering processes on firefighter protective clothing. These samples include facsimile representations of clothing that included seams and protected edges as might be found in manufactured clothing. In order to obtain the needed number of test specimens for selected performance tests, a variety of different samples were constructed.

Evaluation of Soiling Removal

Method for Soiling Fabrics. There are no established methods for evaluating the effectiveness of laundry processes in removing soils in protective apparel. A suitable method for modification was identified in American Association for Textile Chemists and Colorists (AATCC) Test Method 123-2000, *Carpet Soiling: Accelerated Soiling Method*. This test method provides procedures for determining the propensity for soiling of carpet samples using synthetic soil and a tumbling method. This method offered a means for reproducibly soiling outer shell fabrics.

Modifications were made to the AATCC 123 test method for soiling outer shell fabrics by the University of Alberta. The synthetic soil formulation used in AATCC 123 was used as specified; however, changes were made in the procedures for contacting outer shell fabrics with the synthetic soil since it was found that some aspects of the AATCC procedures would not uniformly soil fabrics as intended for carpet samples.

The actual ingredient list for the synthetic soil is provided in Table 4.

Table 4 – Synthetic Soil Formulation

Ingredient	% by Weight
Peat moss (dark)	38
Portland cement	17
Kaolin clay	17
Silica (200 mesh)	17
Carbon black	1.75
Red iron oxide	0.50
Mineral oil	8.75

All dry ingredients were mixed together thoroughly before adding mineral oil. The mixture was then baked at 122°F (50°C) for 8 hours before use.

The sample fabrics were preconditioned by washing using the procedures in AATCC 135, *Dimensional Changes in Automatic Home Laundering of Woven and Knit Fabrics*, using Machine Cycle 1 (sturdy/cotton), Wash Temperature V (160°F), and Laundering Condition Ai (tumble drying/high heat), to remove some of the finishes that applied to the fabrics during their processing. These finished retard the wetting of fabric and the adhesion of soils. Nevertheless, the effects of these finishes are generally reduced by both washing and wear of the garment. In some cases, water-repellent finishes are reapplied periodically to limit soiling of outer shell fabrics. Some preconditioned (washed) fabric outer shell samples were retained as a laundered "control" since washing reduces the brightness and causes some color changes in fabrics, even without soiling.

The preconditioned fabric soiling was accomplished using a Launder-Ometer (specified in AATCC 61-2003, *Colorfastness to Laundering, Home and Commercial: Accelerated*). A Launder-Ometer is a special washing machine that is typically used in the testing of fabrics for colorfastness. It consists of a machine that rotates closed canisters in a thermostatically controlled water bath (see Figure 3).

Figure 3 – Example of Launder-Ometer used in Soiling Removal Test

For the fabric soiling, 6-inch square specimens of preconditioned fabric were placed inside lined canisters with 100 grams of synthetic soil and 50 stainless steel balls measuring ¼ inch (6 mm) in diameter. The steel balls were used to provide physical rubbing of the soil against the fabric specimen inside the canister to help increase the level of soiling. The fabric specimens were tumbled inside the Launder-Ometer without using the water bath at a rotational speed of 40 rpm for a period of 45 minutes. This process was repeated for three sets of two different specimens for each outer shell fabric.

Following the conclusion of soiling period, the soiled samples were removed from the canister and any loosely adhering soil was removed by light brushing. The samples were divided with half of the samples being subjected to one cycle of the Esporta laundering process and the other half to one cycle of the conventional laundering process. Additional soiled samples were retained to serve as samples soiled, but not laundered.

Procedures for Comparing Soiling Removal. The removal of soiling was determined in three different ways:

1. A visual comparison was made between the soiled and unsoiled (control) specimens
2. A gray scale change was assigned to each specimen (a gray scale is a way of quantifying the change in a material color relative to its original color)
3. Spectrophotometric measurements were made comparing the soiled and unsoiled (control) specimens.

The findings using each approach were used for reporting the results in soiling removal. Visual comparison were documented using photographs of the laundered fabrics against the "standard" fabric (not preconditioned and not subjected to the laundering process) and against control fabric samples.

A Gray Scale determination was applied to each specimen relative the test. Gray scale determinations are used in colorfastness testing to determine changes in color as the result of exposure to different stimuli (UV light, washing, rubbing, perspiration, etc.). The Gray Scale consists of pairs of standard gray chips with the pairs representing progressive differences in color or contrast that then correspond to numerical ratings. AATCC Evaluation Procedure 1, *Gray Scale for Color Change*, uses numerical ratings from 1 to 5 with intermediate readings. These ratings have the interpretations as shown in Table X using the standardized gray chips provided by the American Association of Textile Chemists and Colorists.

Table 5 – Gray Scale for Rating Color Change

Grade	Interpretation
5	Negligible or no color change as shown in Gray Scale Step 5
4.5	Change in color equivalent to Gray Scale Step 4.5
4	Change in color equivalent to Gray Scale Step 4.0
3.5	Change in color equivalent to Gray Scale Step 3.5
3	Change in color equivalent to Gray Scale Step 3.0
2.5	Change in color equivalent to Gray Scale Step 2.5
2	Change in color equivalent to Gray Scale Step 2.0
1.5	Change in color equivalent to Gray Scale Step 1.5
1	Change in color equivalent to Gray Scale Step 1.0

A different set of contrasting gray chips uses a similar scale but rates fabrics for staining. Both color changes and staining ratings were applied to the control, soiled, and test outer shell fabric specimens. These semi-quantitative ratings were made using two different observers.

Spectrophotometric measurements were made on control, soiled, and test outer shell fabric specimens using principles described in AATCC Evaluation Procedure 6, *Instrumental Color Measurement*. The color of fabric specimens was measured using reflectance methods consistent with procedures in ASTM E 308, Standard Test Method for Comparing the Colors of Objects by Using the CIE System, and Publication CIE No. 15.2(1986), *Colorimetry* [2nd Edition, Commission Internationale de l'Esclairage (EIE), Vienna, Austria].

Two types of spectrophotometric measurement approaches were used. The first approach involved the characterization of specimen color using the standard rectangular grid where following measurements were made:

- L* – color intensity (ratio of luminance to incident luminance)
- a* – color coordinate representing red-green axis, positive changes indicate a shift to red
- b* – color coordinate representing blue-yellow axis, positive changes indicate a shift to yellow

In addition, specimen color was characterized using chromaticity and hue with a 360 degree scale with the a* axis being 0 degrees and the b* positive axis at 90 degrees. Color change was represented by the following measurements:

- ΔE* – composite change in color intensity, chromaticity, and hue
- ΔC* – change in chromaticity
- ΔH* – change in hue
- ΔL* – change in color intensity

The latter measurements best characterized the actual differences between standard and test specimens. Additional details on these measurements can be found in AATCC Evaluation Procedure 6 and ASTM E 308.

Since specimen color is affected by the type of illumination, an illumination source of D65 was used, which is representative of average outdoor sunlight. A viewing angle of 10 degrees was also used for all color measurements.

Evaluation of Chemical Contaminant Removal

Sample Conditioning and Specimen Preparation. Several one meter square sections of both outer shell materials were laundered for 5 cycles in accordance with AATCC 135, *Dimensional Changes in Automatic Home Laundering of Woven and Knit Fabrics*, using Machine Cycle 1 (sturdy/cotton), Wash Temperature V (160^{o}F), and Laundering Condition Ai (tumble drying/high heat), to remove or reduce process finishes and better represent the fabrics in a condition of fire service use. Specimens of both outer shells, measuring 10 cm (4 in.) square, were then removed from the laundered fabric and used in the testing for chemical contamination removal.

For each outer shell material and each laundering process combination, a total of 21 specimens in sets of 3 specimens were taken and used as follows:

- Three sets of these specimens for each fabric were tack sewn onto the laundered pieces of outer shell material of the same type as the specimens (outer shell specimens were tacked onto like outer shell samples). These specimens were then subjected to one complete cycle of the respective laundering process. These specimens were removed from the support fabric piece and retained as "control" specimens for the analysis.

- Three different sets of these specimens for each fabric were subjected to the chemical contamination procedures described below and were similarly tacked onto laundered, but uncontaminated samples of like outer shell material. The specimens were then subjected to one complete cycle of the respective laundering process. These contaminated/washed specimens were used for assessing retention of chemical contaminants in the fabric following laundering and were referred to as the "test" specimens.

- One remaining set of specimens for each fabric was subjected to the chemical contamination procedures described below, but were not washed. These specimens became the contaminated/unwashed specimens for the analysis and were referred to as the “baseline” specimens.

Chemical Contamination Procedures. Three different chemicals were selected for representing a range of chemical contaminants. The selection of these chemical was based on the earlier work described in the U.S. Fire Administration report, “Research, Testing and Analysis on the Decontamination of Firefighting Protective Clothing and Equipment,” USFA Contract No. EME-96-CO-0505 (February 1999). In this study, three of the six chemicals used in the USFA study were selected to give a range of volatility and chemical properties as selected by the University of Alberta. The pertinent properties of these chemicals are provided in Table 6.

Table 6 – Properties of Selected Chemical Contaminants

Chemical CAS No.	**State**	**Boiling Pt. (^oC)**	**Vap. Press. (mm Hg)**	**Uses**	**Hazards**
Anthracene 120-12-7 $C_6H_4(CH)_2C_6H_4$	Solid	340	~ 0	Dyes, printing, byproduct of combustion	Carcinogen
Dioctyl Phthalate 117-81-7 $C_6H_4[COOCH_2CH\text{-}(C_2H_5)C_4H_9]_2$	Liquid	231	1.32	Common plasticizer	Carcinogen; Irritant
Ethyl Benzene 100-41-4 $C_6H_5C_2H_5$	Liquid	136	126	Solvent, intermediate in plastic processes	Highly toxic by inhalation and skin absorption; irritant; flammable

A mixture of the three chemicals was prepared using the following ingredients:

1 grams of anthracene (5000 ppm)
2.05 ml of dioctyl phthalate (10,000 ppm)
2.3 ml ethyl benzene (10,000 ppm)
280 ml dichloromethane

The three sets of “Contaminated/Washed” specimens were immersed in the mixture for 5 minutes, suspended, and allowed to dry in a laboratory hood. The same procedures were also applied to the sets of “Contaminated/Unwashed” specimens. These specimens were kept in a refrigerator until laundered or analyzed. Under these conditions, the specimens had evaporated to dryness.

The three sets of “Contaminated/Washed” specimens for each outer shell material were then subjected to the respective laundering process, and then refrigerated after laundering before analysis. The one set of “Contaminated/Unwashed” specimens for each fabric were analyzed at a similar time as the “Contaminated/Washed” specimens.

Analysis Procedures. Prior to analysis, 200 µL of dichloromethane and 2 µL of decane (used as an internal standard) were added to each specimen in a glass container with the container and specimen agitated for 30 seconds. The specimens were analyzed using a gas chromatograph (Model HP 5880 A Series gas chromatograph equipped with a flame ionization detector) using the following test parameters:

Column:	30 meter DB wax column of internal diameter 0.53 mm
Flowrate (helium):	5mL/minute
Initial oven temperature:	60°C for 2 minutes
Temperature ramp:	30°C/minute
Final oven temperature:	250°C for 13 minutes
Temperature program:	30°C/minute
Detector temperature:	280°C
Injection temperature:	260°C

A synthetic mixture containing 0.011 g of anthracene, 20 µL of ethyl benzene, 20 µL of octyl phthalate and 20 µL of decane (as internal standard) was prepared in 2 mL of dichloromethane. Samples (1 µL) of the mixture were injected into the gas chromatograph. These concentrations were chosen to be close to the concentration of the contaminants in the solution in which the fabric specimens were immersed. Peaks were identified as follows:

Retention Time	**Due to**
3.75 minutes	Ethyl benzene
4.77 minutes	Decane (internal standard)
8.97 minutes	Anthracene
19.71 minutes	Dioctyl phthalate

The experimental samples were also analyzed by injecting 1 µL into the gas chromatograph. The peaks were integrated electronically and normalized using the internal standard. The concentration of the identified contaminant present in the sample was calculated from the values from the synthetic mixture and the volumes of solvent used to dissolve the samples.

Calculations. The following calculations were made:

- The average contaminant concentration for each target contaminant shall be determined for each set of specimens (control, baseline, and test) for each fabric

- The decontamination efficiency for each target chemical shall be determined based on the following formula:

  Decontamination efficiency = $\{[(C_b - C_c) - (C_t - C_c)]/(C_b - C_c)\} \times 100$

  Where:

  C_c = Average contaminant concentration in control specimens

C_b = Average contaminant concentration in baseline specimens

C_t = Average contaminant concentration in test specimens

Evaluation of Laundry Effects on Protective Clothing Properties

NFPA 1851, *Standard on Selection, Care, and Maintenance of Structural Fire Fighting Protective Ensembles* (2001 Edition), describes procedures for evaluating laundry effects on key protective clothing properties in Appendix section A.5.1.4 of the standard. These procedures were used as the basis for this portion of the study evaluation. The general approach involved constructing composite samples that appeared as large envelops where the outer material was the outer shell and the inner materials were representative of a liner consisting of the moisture barrier and thermal barrier. These materials were subjected to multiple laundering individually using each laundering process and then specimens were taken for specific performance tests. Specific procedures included:

1. Surrogate clothing samples were prepared for each composite where a lining sample consisting of moisture barrier and thermal barrier material was sandwiched between outer shell layers in a pocket like enclosure. In the basic sample configuration, the overall outer shell pocket measured 66 cm (26-inch) square and used hook and loop closure sewn to the ends to provide a method of folding the sample in half and securing the two opposite ends. Different types of samples were constructed to provide adequate material for required material, seam, and component test specimens; these included.

   - Composite samples with the moisture barrier layer having a seam that divided that layer in two.

   - Composite samples with each layer (outer shell, moisture barrier, and thermal barrier) having a seam that divided the respective layer in two.

   - Composite samples that had four (4) 26 inch strips of trim sewn to the exterior of the outer shell layer, equally spaced over the sample.

   - The warp direction of the outer shells was indicated on both sides of each sample to aid the laboratories in identifying the correct material direction for some tests that are direction dependent.

2. The specified surrogate samples of protective clothing were subjected to 25 cycles of washing separately for both the Esporta and conventional laundering process. A total of 25 wash cycles was selected as the maximum number of washing that firefighter protective garment could experience over their service life.

3. Specimens were then taken from unwashed and laundered samples to perform the following tests specified in Table 7 in accordance with NFPA 1971 (2000 edition). The number and size of the test specimen requirements were based on the requirements indicated in Table 8.

Table 7 – Testing Procedures for Evaluating Effects of Laundering Process on Protective Clothing

Layer or Component	Performance Property	Test Method	Data Reported
Composite	Thermal Protective Performance	NFPA 1971, Section 6-10	TPP rating
Outer shell	Flame resistance	ASTM D 6413	Afterflame time Char length Burning behavior
	Tear resistance	ASTM D 5733	Tear strength
	Breaking strength	ASTM D 5034	Breaking strength
	Water absorption resistance	NFPA 1971, Section 6-23	% Water absorption
Outer shell seams	Seam strength	ASTM D 1683	Seam strength
Moisture barrier	Flame resistance	ASTM D 6413	Afterflame time Char length Burning behavior
	Tear resistance	ASTM D 5733	Tear strength
Moisture barrier seams	Seam strength	ASTM D 1683	Seam strength
	Gasoline penetration	ASTM F 903	Pass/fail results
	Viral penetration	ASTM D 1671	Pass/fail results
Thermal barrier	Flame resistance	ASTM D 6413	Afterflame time Char length Burning behavior
	Tear resistance	ASTM D 5733	Tear strength
Thermal barrier seams	Seam strength	ASTM D 1683	Seam strength
Reflective trim	Retroreflection	NFPA 1971, Section 6-46	Coefficient of retroreflection

Table 8 – Specimen Requirements for Laundering Effects

Layer or Component	Performance Property	Needed Specimens
Composite	Thermal Protective Performance	3 – 6 x 6 inch squares
Outer shell	Flame resistance	10 – 3 x 12 inch rectangles (in both material directions)
	Tear resistance	10 – 3 x 6 inch rectangles (in both material directions)
	Breaking strength	10 – 4 x 6 inch rectangles (in both material directions)
	Water absorption resistance	3 – 8 x 8 inch squares
Outer shell seams	Seam strength	5 – 4 x 6 seam rectangles
Moisture barrier	Flame resistance	10 – 3 x 12 inch rectangles (in both material directions)
	Tear resistance	10 – 3 x 6 inch rectangles (in both material directions)
Moisture barrier seams	Seam strength	5 – 4 x 6 seam rectangles
	Gasoline (Fuel C) penetration	3 – 3 inch squares
	Viral penetration	3 – 3 inch squares
Thermal barrier	Flame resistance	10 – 3 x 12 inch rectangles (in both material directions)
	Tear resistance	10 – 3 x 6 inch rectangles (in both material directions)
Thermal barrier seams	Seam strength	5 – 4 x 6 seam rectangles
Reflective trim	Retroreflection	6 – 24 inch long strips

Testing was performed by the University of Alberta and Intertek Testing Services.

RESULTS AND DISCUSSION

Soiling Removal

Visual Comparison. Figures 4 through 9 provide photographs of the original outer shell fabrics compared to the soiled outer shell fabric and after each laundering process.

It must be noted that the photographs do not necessary provide true representation of color since light conditioning can change during the photography and the shutter of the digital camera automatically adjusts for color differences, in turn affecting the true color.

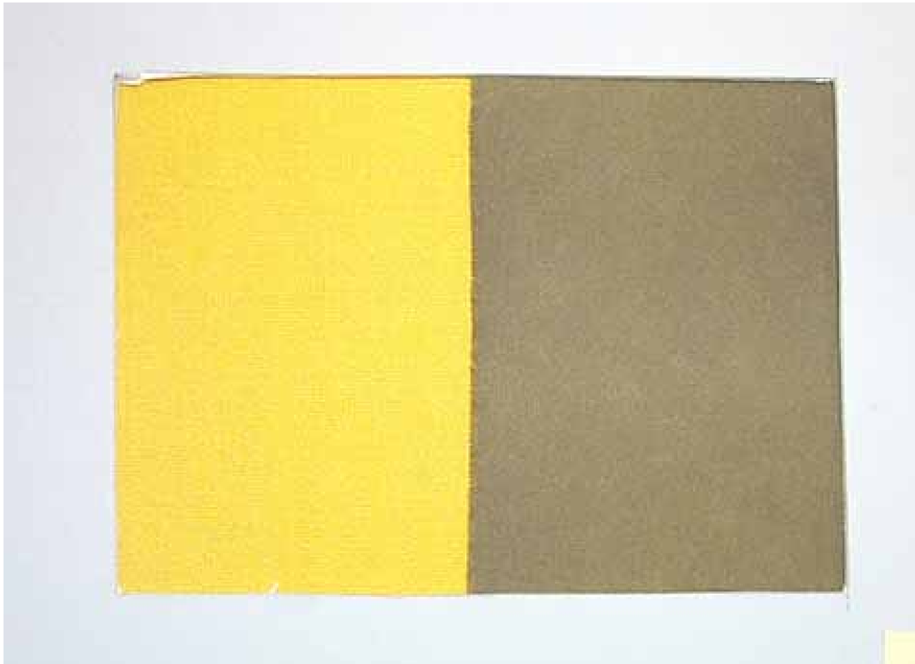

Figure 4 – Original / Soiled Nomex Outer Shell Specimens

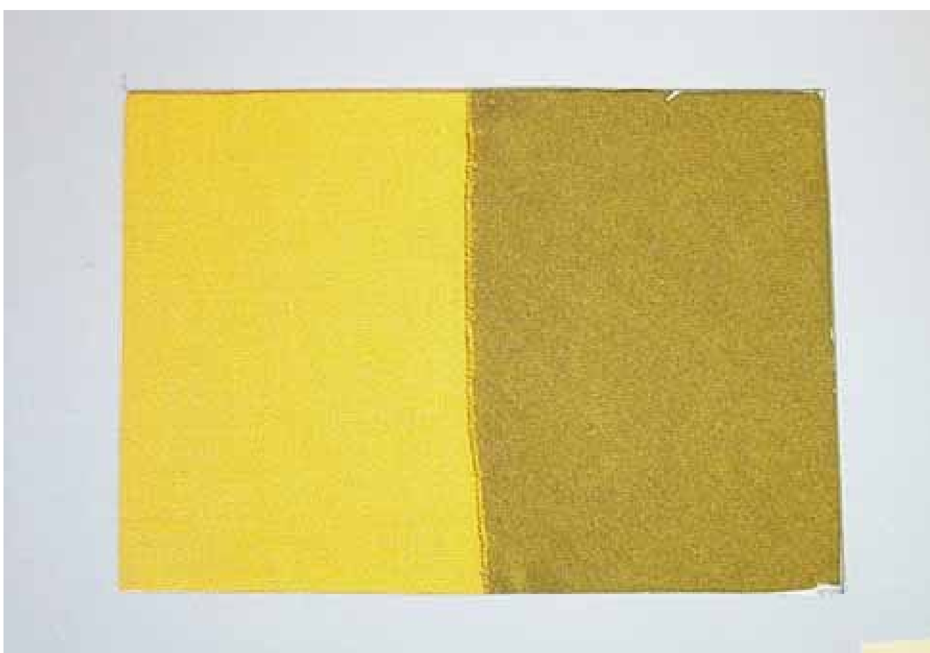

Figure 5 – Original / Conventional Laundered, Soiled Nomex Outer Shell Specimens

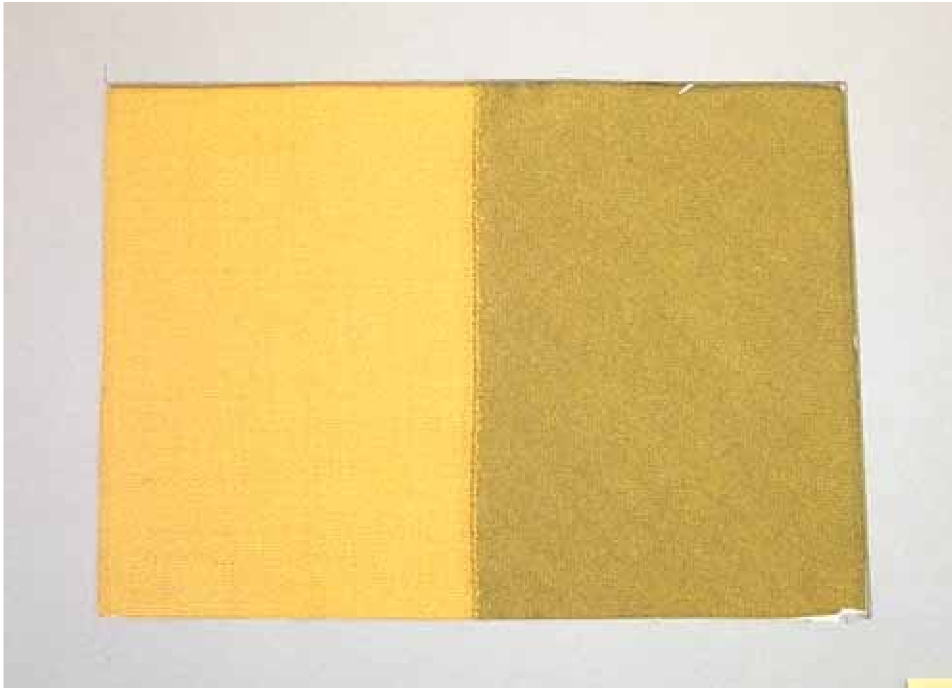

Figure 6 – Original / Esporta Laundered, Soiled Nomex Outer Shell Specimens

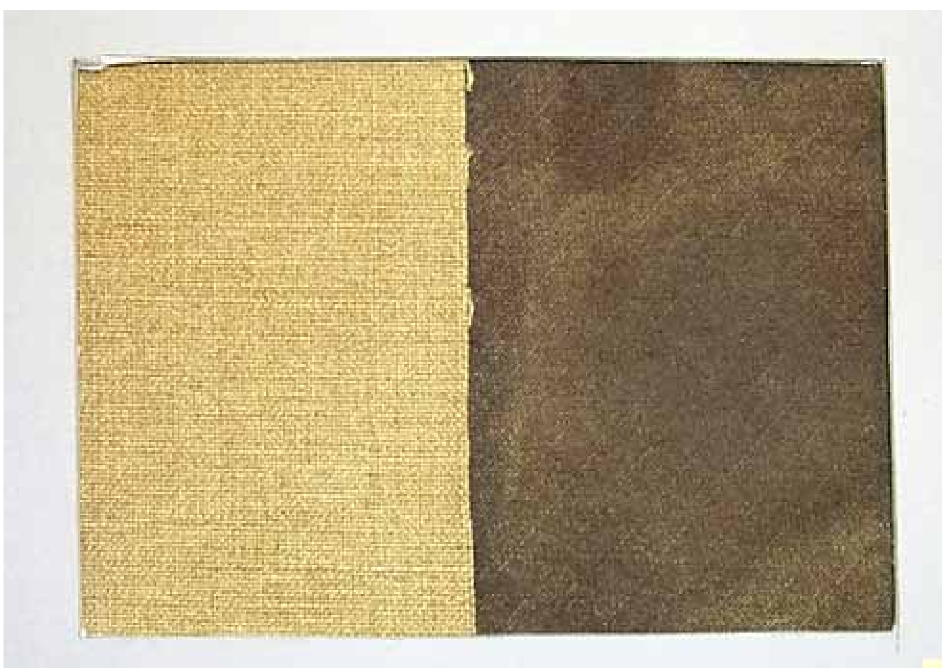

Figure 7 – Original / Soiled PBI-Kevlar Outer Shell Specimens

Figure 8 – Original / Conventional Laundered, Soiled PBI-Kevlar Outer Shell Specimens

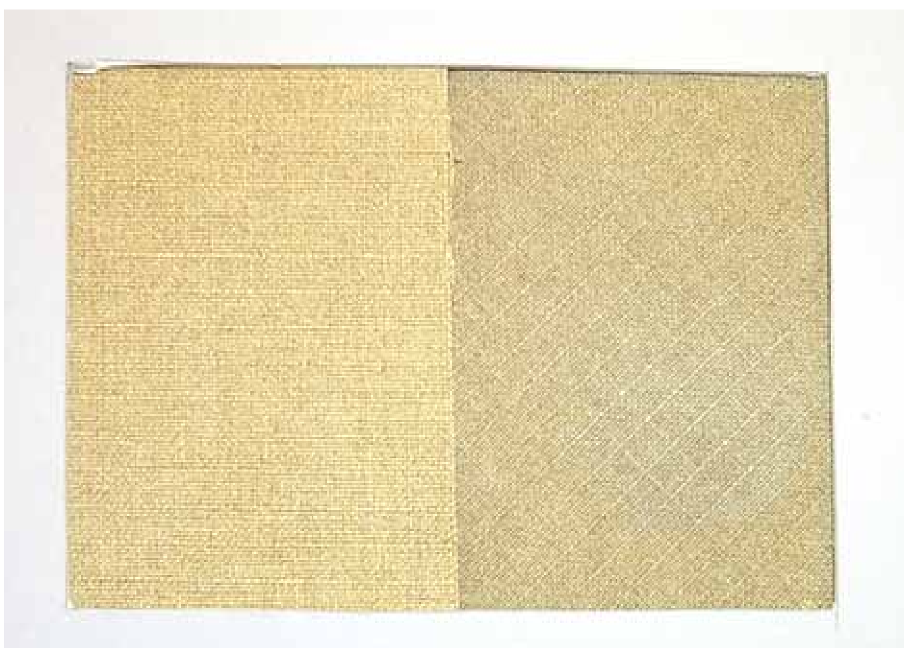

Figure 9 – Original / Esporta Laundered, Soiled PBI-Kevlar Outer Shell Specimens

Gray Scale Ratings. The application of Gray Scale ratings were also used in discriminating the removal of soiling. Theses ratings are reported in Table 9.

Table 9 – Gray Scale Color Rating for Soiled and Laundered Outer Shell Specimens Relative to Unsoiled, Unlaundered Fabric

Outer Shell	Condition*	Esporta Process		Conventional Process	
		Specimen No.	Gray Scale Rating**	Specimen No.	Gray Scale Rating**
Nomex	Unsoiled	E1	4	C1	4
		E2	4		
	Soiled	E1-1	1.5	C1-1	1.5
		E1-2	1.5	C1-2	1.5
		E2-1	2	C2-1	1.5
		E2-2	2	C2-2	1.5
		E3-1	2	C3-1	1.5
		E3-2	2	C3-2	1.5
PBI/Kevlar	Unsoiled	E1	4.5	C1	4.5
		E2	4.5	C2	4.5
		E3	5	C3	4.5
	Soiled	E1-1	3	C1-1	2.5
		E1-2	3	C1-2	2.5
		E2-1	3	C2-1	2.5
		E2-2	3	C2-2	2.5
		E3-1	3	C3-1	2.5
		E3-2	3	C3-2	2.5

* All fabric specimens were first washed 5 times per AATCC 135 (1, V, Ai)
** Gray scale is relative to standard fabric (washed as above)

All of the Gray Scale color ratings in Table 9 are relative to the unsoiled outer shell materials that had not been subjected to either laundering process. If instead, the comparison was made to the unsoiled but laundered fabric, then there would be a slight improvement in the ratings. The new average ratings would be as shown in Table 10 below:

Table 10 – Average Gray Scale Ratings for Soiled and Laundered Outer Shell Specimens Relative to Unsoiled, Laundered Fabric

Outer Shell	Esporta Process	Conventional Process
Nomex	2 to 2.5	1.5 to 2
PBI/Kevlar	3.5	2 to 3

Likewise, if staining Gray Scale ratings are applied, similar results are obtained as shown in Table 10.

Spectrophotometric Measurements. Measurement of specimen color using reflectance (spectrophotometer) measurements provided a more quantitative assessment of soiling removal. Color coordinates were measured for all of the specimens using both the rectangular and angular color coordinate systems. These results are provided by outer shell fabric in Table 11 and 12. The principal color coordinates of L*, a*, and b* provide the specific characterization of the specimen color, whereas ΔE*, ΔC*, ΔH*, and ΔL* represent different ways of showing the change in color relative to the soiled, unlaundered fabrics. Smaller changes in the latter values would be indicative of more soil removal.

Table 11 – Spectrophotometric Measurements on Nomex Outer Shell Specimens

Specimen	**L***	**a***	**b***	**ΔE***	**ΔC***	**ΔH***	**ΔL***
Standard	72.44	22.11	79.06				
Unsoiled E1	76.22	19.30	87.91	10.03	7.91	4.87	3.78
Unsoiled E2	76.19	19.44	88.20	10.24	8.22	4.80	3.75
Unsoiled C1	75.99	19.33	88.12	10.12	8.12	4.89	3.56
Soiled E1-1	49.99	7.90	47.69	41.11	-33.76	6.84	-22.45
Soiled E1-2	50.42	8.11	48.52	40.17	-32.90	6.80	-22.02
Soiled E2-1	51.76	8.52	49.86	38.27	-31.51	6.67	-20.67
Soiled E2-2	51.9	8.47	50.07	38.05	-31.31	6.79	-20.54
Soiled E3-1	51.55	8.27	49.06	39.09	-32.34	6.75	-20.88
Soiled E3-2	52.99	8.79	51.01	36.64	-30.33	6.65	-19.45
Average	***51.44***	***8.34***	***49.37***	***38.89***	***-32.03***	***6.75***	***-21.00***
Soiled C1-1	46.35	6.82	42.14	47.72	-39.40	6.65	-26.09
Soiled C1-2	45.86	6.73	41.34	48.64	-40.21	6.52	-26.57
Soiled C2-1	46.32	6.89	41.57	48.16	-39.96	6.37	-26.11
Soiled C2-2	47.28	6.76	42.64	46.85	-38.92	6.88	-25.16
Soiled C3-1	46.95	6.79	41.73	47.72	-39.81	6.56	-25.49
Soiled C3-2	48.21	7.15	43.47	45.58	-38.04	6.60	-24.22
Average	***46.83***	***6.86***	***42.15***	***47.85***	***-39.39***	***6.60***	***-25.61***

Table 12 – Spectrophotometric Measurements on PBI/Kevlar Outer Shell Specimens

Specimen	L*	a*	b*	ΔE*	ΔC*	ΔH*	ΔL*
Standard	59.52	3.93	30.05				
Unsoiled E1	58.17	3.64	28.72	1.92	-1.36	0.12	-1.35
Unsoiled E2	57.77	3.75	28.88	2.11	-1.19	0.03	-1.75
Unsoiled E3	59.42	3.90	29.41	0.65	-0.64	-0.06	-0.1
Average	***58.45***	***3.76***	***29.00***	***1.56***	***-1.06***	***0.03***	***-1.07***
Unsoiled C1	59.84	3.95	30.32	0.42	0.27	0.01	0.33
Unsoiled C2	60.27	3.66	30.33	0.85	0.24	0.31	0.76
Unsoiled C3	60.78	3.62	31.15	1.70	1.06	0.44	1.26
Average	***60.30***	***3.74***	***30.60***	***0.99***	***0.52***	***0.25***	***0.78***
E1-1	48.82	2.45	20.72	14.27	-9.44	0.31	-10.7
E1-2	50.48	1.82	20.66	13.21	-9.57	1.05	-9.04
E2-1	50.53	1.98	21.22	12.75	-9.00	0.94	-8.99
E2-2	50.14	1.94	21.11	13.11	-9.11	0.98	-9.37
E3-1	50.06	2.32	20.68	13.41	-9.50	0.46	-9.46
E3-2	51.47	1.45	20.69	12.59	-9.57	1.51	-8.05
Average	***50.25***	***1.99***	***20.85***	***13.22***	***-9.37***	***0.88***	***-9.27***
C1-1	46.16	1.97	19.00	17.45	-11.21	0.65	-13.36
C1-2	48.55	2.32	20.17	14.85	-10.00	0.38	-10.97
C2-1	47.45	1.73	18.94	16.55	-11.29	0.93	-12.07
C2-2	45.58	1.82	18.05	18.52	-12.17	0.69	-13.94
C3-1	48.68	2.24	19.85	14.98	-10.33	0.44	-10.84
C3-2	47.41	1.84	18.39	16.95	-11.83	0.72	-12.11
Average	***47.31***	***1.99***	***19.07***	***16.55***	***-11.04***	***0.64***	***-12.22***

Overall Comparison of Soiling Removal. Figures 10 and 11 summarize the color change and spectrophotometric measurements in comparing the laundering process removal of soiling relative to unlaundered, unsoiled fabric. Based on the three types of analysis for soiling removal, the following observations can be made:

- The method used to soil outer shell fabrics was found to be relatively aggressive in darkening the fabrics. In all cases, the outer shell materials remained permanently discolored following laundering by both procedures.

- Both fabrics appeared to be equally soiled as shown visually, but the PBI/Kevlar outer shell appeared to have more soiling removed through laundering than the Nomex outer shell fabric.

- Visual results show that the Esporta laundering process to remove slightly more soiling than the conventional laundering process. These results were also borne out in the Gray Scale ratings for both sets of outer shell fabrics.

- The spectrophotometric measurements of color for soiled, laundered specimens showed specific differences in the ability of the laundering processes to remove soiling when compared to unsoiled, unlaundered specimens. Significant differences (larger changes) were noted for ΔE^*, ΔC^*, and ΔL^* for the Esporta laundering process as compared to the conventional laundering process for both outer shells. Smaller differences were noted for ΔH^* (hue) for the conventional laundering process, but these differences were not found to be significant.

Chemical Contaminant Removal

Detection of Chemical Contaminants. As previously described, the effectiveness of each laundering process in removing chemical contaminants was based on efficiencies for removing specific chemicals in preconditioned outer shell materials. This testing included determining any chemical contaminant that may have already been in the fabric samples as introduced by finishing or laundering for control specimens and also determining the maximum concentration that stayed in the fabric without being subjected to the laundering process (baseline specimens). The measured chemical concentrations are reported for all test samples in Table 13 and for control and baseline specimens in Table 14.

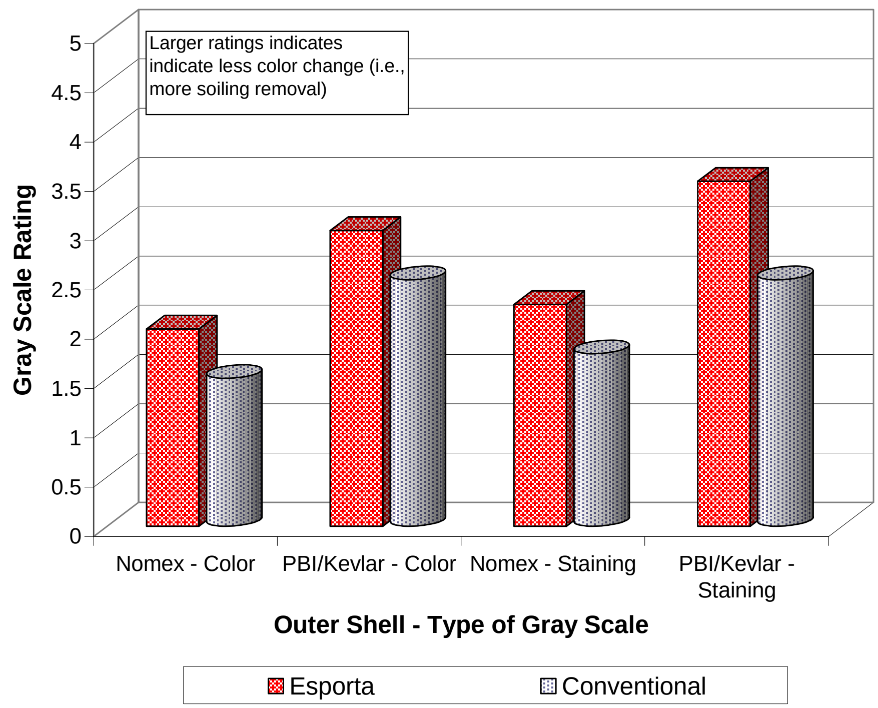

Figure 10 – Gray Scale Ratings for Soiling Removal by Laundering Processes

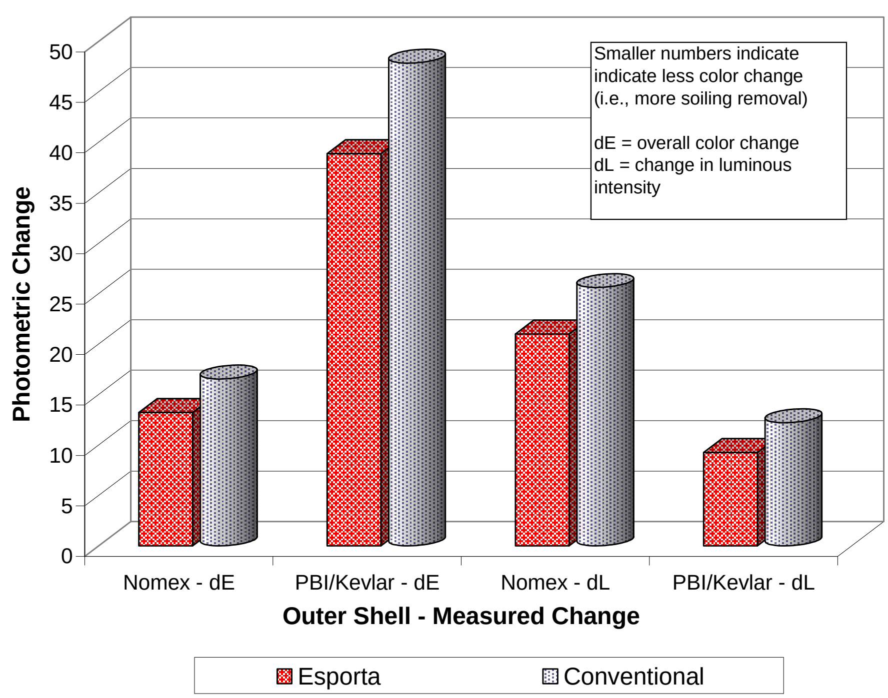

Figure 11 – Spectrophotometric Color Changes for Soiling Removal by Laundering Processes

Table 13 – Chemical Amounts Detected in "Test" Outer Shell Fabric Specimens*

Outer Shell	Type of Sample	Laundry Process	Specimen	Ethyl Benzene (mL)	Anthracene (mg)	Dioctyl Phthalate (mL)
Nomex	Test	Esporta	A1-1	n/o**	1.82	8.5
			A1-2	n/o	1.86	10.1
			A1-3	n/o	2.23	9.1
			A2-1	n/o	1.92	11.9
			A2-2	n/o	1.76	10.7
			A2-3	n/o	1.78	9.2
			A3-1	n/o	1.74	9.4
			A3-2	n/o	1.86	13.9
			A3-3	n/o	1.91	9.4
PBI/Kevlar	Test	Esporta	B1-1	n/o	2.31	10.5
			B1-2	n/o	1.86	12.0
			B1-3	n/o	2.38	9.8
			B2-1	n/o	1.66	11.4
			B2-2	n/o	1.34	12.2
			B2-3	n/o	1.78	7.8
			B3-1	n/o	1.29	11.1
			B3-2	n/o	1.91	11.1
			B3-3	n/o	1.78	9.1
Nomex	Test	Conv.	C1-1	n/o	3.77	11.9
			C1-2	n/o	3.86	12.1
			C1-3	n/o	2.62	14.2
			C2-1	n/o	2.36	15.6
			C2-2	n/o	2.28	18.2
			C2-3	n/o	2.02	19.8
			C3-1	n/o	2.05	19.5
			C3-2	n/o	1.82	15.0
			C3-3	n/o	2.34	10.3
PBI/Kevlar	Test	Conv.	D1-1	n/o	1.86	11.2
			D1-2	n/o	2.18	11.0
			D1-3	n/o	2.04	15.3
			D2-1	n/o	2.49	17.0
			D2-2	n/o	2.38	17.7
			D2-3	n/o	2.44	10.1
			D3-1	n/o	2.17	17.3
			D3-2	n/o	2.26	13.1
			D3-3	n/o	2.17	14.4

* Amount detected in 2 mL of extract solvent (dichloromethane)
** Not observed (detected)

Table 14 – Chemical Amounts Detected in Control and Baseline Outer Shell Fabric Specimens*

Outer Shell	Type of Sample	Laundry Process	Specimen	Ethyl Benzene (mL)	Anthracene (mg)	Dioctyl Phthalate (mL)
Nomex	Control	Esporta	E1-1	n/o**	n/o	n/o
			E1-2	n/o	n/o	n/o
			E1-3	n/o	n/o	n/o
			E2-1	n/o	n/o	n/o
			E2-2	n/o	n/o	n/o
			E2-3	n/o	n/o	n/o
			E3-1	n/o	n/o	n/o
			E3-2	n/o	n/o	n/o
			E3-3	n/o	n/o	n/o
PBI/Kevlar	Control	Esporta	F1-1	n/o	n/o	n/o
			F1-2	n/o	n/o	n/o
			F1-3	n/o	n/o	n/o
			F2-1	n/o	n/o	n/o
			F2-2	n/o	n/o	n/o
			F2-3	n/o	n/o	n/o
			F3-1	n/o	n/o	n/o
			F3-2	n/o	n/o	n/o
			F3-3	n/o	n/o	n/o
Nomex	Control	Conv.	G1-1	n/o	n/o	n/o
			G1-2	n/o	n/o	n/o
			G1-3	n/o	n/o	n/o
			G2-1	n/o	n/o	n/o
			G2-2	n/o	n/o	n/o
			G2-3	n/o	n/o	n/o
			G3-1	n/o	n/o	n/o
			G3-2	n/o	n/o	n/o
			G3-3	n/o	n/o	n/o
PBI/Kevlar	Control	Conv.	H1-1	n/o	n/o	n/o
			H1-2	n/o	n/o	n/o
			H1-3	n/o	n/o	n/o
			H2-1	n/o	n/o	n/o
			H2-2	n/o	n/o	n/o
			H2-3	n/o	n/o	n/o
			H3-1	n/o	n/o	n/o
			H3-2	n/o	n/o	n/o
			H3-3	n/o	n/o	n/o
Nomex	Baseline	N/A	I-1	18.5	19.2	15.9
			I-2	17.5	14.7	19.0
			I-3	18.4	17.2	18.6
PBI/Kevlar	Baseline	N/A	J-1	19.1	17.2	17.8
			J-2	18.1	18.7	18.9
			J-3	18.2	19.2	16.9

* Amount detected in 2 mL of extract solvent (dichloromethane); ** Not observed (detected)

Decontamination Efficiencies. The decontamination efficiency for each outer shell fabric, each selected chemical contaminant, and each laundering process using the information provided in Tables 13 and 14. Decontamination efficiency was based on the total average baseline concentration minus the average test concentration for the particular laundering process as determined for each chemical. It was not necessary to factor in the control results, since all measurements show no residual chemical in any laundered, uncontaminated specimens. The results of these calculations are presented in Table 15 and shown in Figure 12.

Table 15 – Decontamination Efficiencies for Outer Shell Fabrics and Laundering Processes by Chemical

Outer Shell Fabric	Laundering Process	Sample Set	Decontamination Efficiency (%)		
			Ethyl Benzene	Anthracene	Dioctyl Phthalate
Nomex	Esporta	1	100.0	88.4	48.2
		2	100.0	89.3	40.6
		3	100.0	89.2	38.9
		Average	***100.0***	***89.0***	***42.6***
	Conventional	1	100.0	79.9	28.6
		2	100.0	87.0	-0.2
		3	100.0	87.8	16.3
		Average	***100.0***	***84.9***	***14.9***
PBI/Kevlar	Esporta	1	100.0	88.1	39.7
		2	100.0	91.3	41.4
		3	100.0	91.0	41.6
		Average	***100.0***	***90.1***	***40.9***
	Conventional	1	100.0	89.0	30.0
		2	100.0	86.7	16.4
		3	100.0	88.0	16.4
		Average	***100.0***	***87.9***	***21.0***

Overall Comparison of Chemical Contaminant Removal. A summary of the decontamination efficiency is provided in Figure 13. A review of the results provides the following observations:

- The decontamination efficiency for the two outer shell fabric varied with the chemical.

- No ethyl benzene was found in any laundered specimens, but was measured in the control samples at a concentration consistent with the initial concentration in solution. The absence of ethyl benzene is not surprising, given its high vapor pressure and likelihood of evaporation.

- Anthracene was more readily removed from outer shell specimens as compared to dioctyl phthalate despite the higher vapor pressure and lower boiling point for dioctyl phthalate. This difference may be explained by the basis that the anthracene is normally a solid (crystals) that while dissolved in the solvent for doping of the outer shell materials, may be subject to precipitation once the carrier solvent evaporated.

- The decontamination efficiency for anthracene was slightly greater for the Esporta laundering process as compared to the conventional laundering process for both outer shell materials.

- The decontamination efficiency for dioctyl phthalate was significant greater for the Esporta laundering process as compared to the conventional laundering process. In the case of the Nomex outer shell material, the Esporta laundering process provided a three fold improvement over the conventional laundering process in removing the chemical. For the PBI/Kevlar outer shell material, the Esporta laundering process was nearly twice as efficient in removing chemical contaminant.

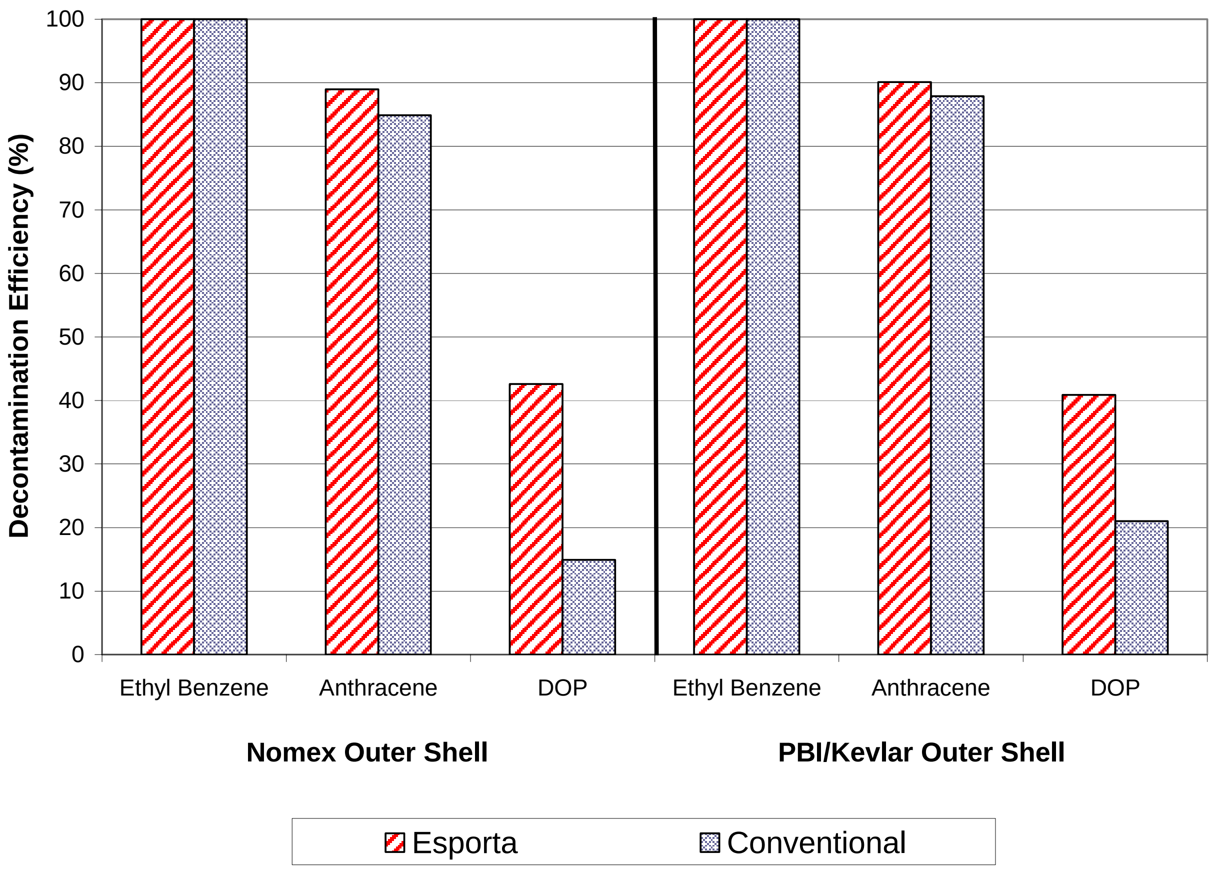

Figure 12 – Comparison of Decontamination Efficiency by Chemical and Laundering Process

Laundering Effects on Key Clothing Performance Properties

General Results. Selected properties recommended in NFPA 1851-2001 were measured for pristine fabric and for fabric specimens removed from surrogate firefighter clothing samples that had been subjected to 25 cycles of each laundering process. The average results for all composites, materials, and seams are provided in Table 16. Specific comparisons by key properties are provided in the following figures:

- Figure 14 – Thermal protective performance
- Figure 15 – Flame resistance, char length, warp direction only
- Figure 16 – Tear resistance, warp direction only
- Figure 17 – Breaking strength
- Figure 18 – Water absorption resistance
- Figure 19 – Trim retroreflection

Comparison of Laundering Effects. The effect of laundering varied with the performance property. In some cases, there was an improvement of performance relative to the unlaundered, pristine fabric. For example, thermal protective performance always improved with composite laundering. Some tear strength values for laundered fabrics were also higher than the unlaundered fabrics, presumably due to shrinkage resulting in higher fabric fiber density. In other cases, a decrease in performance was observed – for the majority of tear resistance test results, tensile strength, seam strength, and water absorption. In several instances, the performance was mixed or unchanged. Mixed or unchanged test results comparing laundered and unlaundered fabrics or seams were found flame resistance and liquid penetration resistance.

- The test data were reviewed for significant differences between pristine, unlaundered fabrics and laundered fabrics using ANOVA and related statistical methods as performed by the University of Alberta. A review of the specific results for testing against the selected protective clothing properties gives the following observations:

- Thermal protective performance was found to improve with laundering. A larger increase was noted for the conventional laundering process as compared to the Esporta process; however, the differences between the laundering processes were not statistically significant. Nevertheless, it can be speculated that slightly higher TPP ratings observed for the conventional laundering process could be due to lofting of the material that occurs from wear between the fabric layers as occurs during washing. This phenomenon would suggest that slightly less wear on firefighter clothing composites is caused by the Esporta laundering process relative to the conventional laundering process.

- In general, afterflame time was not affected by laundering. There was one instance of an elevated afterflame time reported on the Nomex outer shell following the Esporta process, but this result is considered to be an anomaly. However, in the case of the conventional laundering process, several elevated afterflame times were noted for the conventional laundering process for the Crosstech moisture barrier.

Table 16 – Average Test Results for Firefighter Protective Clothing Materials after 25 Cycles of Laundering

Property	Measurement	Composite or Material	Pristine (unlaundered)	Esporta Laundered	Conventionally Laundered	NFPA 1971-2000 Criteria
Thermal protective performance	TPP rating (cal/cm^2)	Defender 750 RT7100 Aralite	45.8	49.8	50.1	≥ 35.0 cal/cm^2
		Kombat 750 Crosstech 2C 3-layer E89	42.7	47.1	48.8	
Flame resistance	Afterflame time (sec)	Defender 750	0.0 (W) 0.0 (F)	0.0 (W) 0.2 (F)	0.0 (W) 0.0 (F)	≤ 2.0 sec
		Kombat 750	0.0 (W) 0.0 (F)	0.0 (W) 0.0 (F)	0.0 (W) 0.0 (F)	
		RT7100	0.0 (W) 0.0 (F)	0.0 (W) 0.0 (F)	0.0 (W) 0.0 (F)	
		Crosstech 2C	0.0 (W) 0.0 (F)	0.0 (W) 0.0 (F)	0.4 (W) 0.4 (F)	
		Aralite	0.0 (W) 0.0 (F)	0.0 (W) 0.0 (F)	0.0 (W) 0.0 (F)	
		3-layer E89	0.0 (W) 0.0 (F)	0.0 (W) 0.0 (F)	0.0 (W) 0.0 (F)	
	Char length (in.)	Defender 750	1.7 (W) 1.9 (F)	2.2 (W) 2.0 (F)	2.0 (W) 2.4 (F)	≤ 4.0 in.
		Kombat 750	0.4 (W) 0.3 (F)	0.3 (W) 0.2 (F)	0.2 (W) 0.3 (F)	
		RT7100	2.4 (W) 2.5 (F)	2.2 (W) 2.2 (F)	2.4 (W) 3.0 (F)	
		Crosstech 2C	2.5 (W) 2.8 (F)	2.8 (W) 2.5 (F)	2.6 (W) 2.8 (F)	
		Aralite	0.4 (W) 0.3 (F)	0.4 (W) 0.4 (F)	0.4 (W) 0.4 (F)	
		3-layer E89	0.4 (W) 0.4 (F)	0.6 (W) 0.3 (F)	0.5 (W) 0.4 (F)	

Table 16 – Average Test Results for Firefighter Protective Clothing Materials after 25 Cycles of Laundering (continued)

Property	Measurement	Composite or Material	Pristine (unlaundered)	Esporta Laundered	Conventionally Laundered	NFPA 1971-2000 Criteria
Tear resistance	Tear force (lb_f)*	Defender 750	67.6 (W) 49.7 (F)	61.6 (W) 38.4 (F)	58.9 (W) 42.0 (F)	≥ 22 lb_f (outer shell fabrics)
		Kombat 750	35.5 (W) 28.5 (F)	32.6 (W) 28.7 (F)	29.9 (W) 29.2 (F)	
		RT7100	33.3 (W) 33.0 (F)	27.6 (W) 29.9 (F)	29.2 (W) 27.4 (F)	≥ 5 lb_f (moisture barrier and thermal barrier fabrics)
		Crosstech 2C	16.4 (W) 16.2 (F)	13.7 (W) 14.1 (F)	13.7 (W) 12.8 (F)	
		Aralite	59.8 (W) 36.2 (F)	50.8 (W) 44.2 (F)	59.1 (W) 48.8 (F)	
		3-layer E89	91.0 (W) 39.8 (F)	88.5 (W) 41.1 (F)	85.4 (W) 41.8 (F)	
Breaking strength	Breaking force (lb_f)*	Defender 750	280.0 (W) 244.5 (F)	263.3 (W) 235.7 (F)	258.4 (W) 215.3 (F)	≥ 140 lb_f
		Kombat 750	256.2 (W) 229.9 (F)	264.5 (W) 238.4 (F)	240.2 (W) 212.8 (F)	
Seam strength	Breaking force (lbf)	Defender 750 seams	254.5	236.7	228.2	≥ 150 lb_f (outer shell seams)
		Kombat 750 seams	184.0	179.2	163.8	
		RT7100 seams	85.2	81.7	78.2	≥ 75 lb_f (moisture barrier and thermal barrier seams)
		Crosstech 2C seams	79.7	78.8	**74.3**	
		Aralite seams	100.4	99.0	95.3	
		3-layer E89 seams	124.5	120.2	110.0	

Table 16 – Average Test Results for Firefighter Protective Clothing Materials after 25 Cycles of Laundering (continued)

Property	Measurement	Composite or Material	Pristine (unlaundered)	Esporta Laundered	Conventionally Laundered	NFPA 1971-2000 Criteria
Water absorption resistance	% water absorption	Defender 750	1.4	23.2	15.3	≤ 30%
		Kombat 750	0.7	**52.5**	**45.0**	
Fuel C penetration resistance	Evidence of visible penetration (penetration time)	RT7100 seams	Not tested; previously qualified as passing test	Cell 1 – none (>60 min) Cell 2 – none (>60 min) Cell 3 – none (>60 min)	Cell 1 – none (>60 min) **Cell 2 – yes (5 min)** **Cell 3 – yes (5 min)**	No penetration of Fuel C within one hour
		Crosstech 2C seams		Cell 1 – none (>60 min) Cell 2 – none (>60 min) Cell 3 – none (>60 min)	Cell 1 – none (>60 min) Cell 2 – none (>60 min) Cell 3 – none (>60 min)	
Viral penetration resistance	Plaque forming units each specimen	RT7100 seams	Not tested; previously qualified as passing test	Cell 1 – 0 Cell 2 – 0 Cell 3 – 0	**Cell 1 – >300** **Cell 2 – >300** **Cell 3 – >300**	No penetration of bacteriophage within one hour
		Crosstech 2C seams		Cell 1 – 0 Cell 2 – 0 Cell 3 – 0	Cell 1 – 0 Cell 2 – 0 Cell 3 – 0	
Trim visibility	Coefficient of retroreflection ($cd/lux/m^2$)	Power Trim	197	**32**	**2**	≥ 100 $cd/lux/m^2$
		Scotchlite Trim	345	238	135	
		Scotchlite Triple Trim	517	520	452	

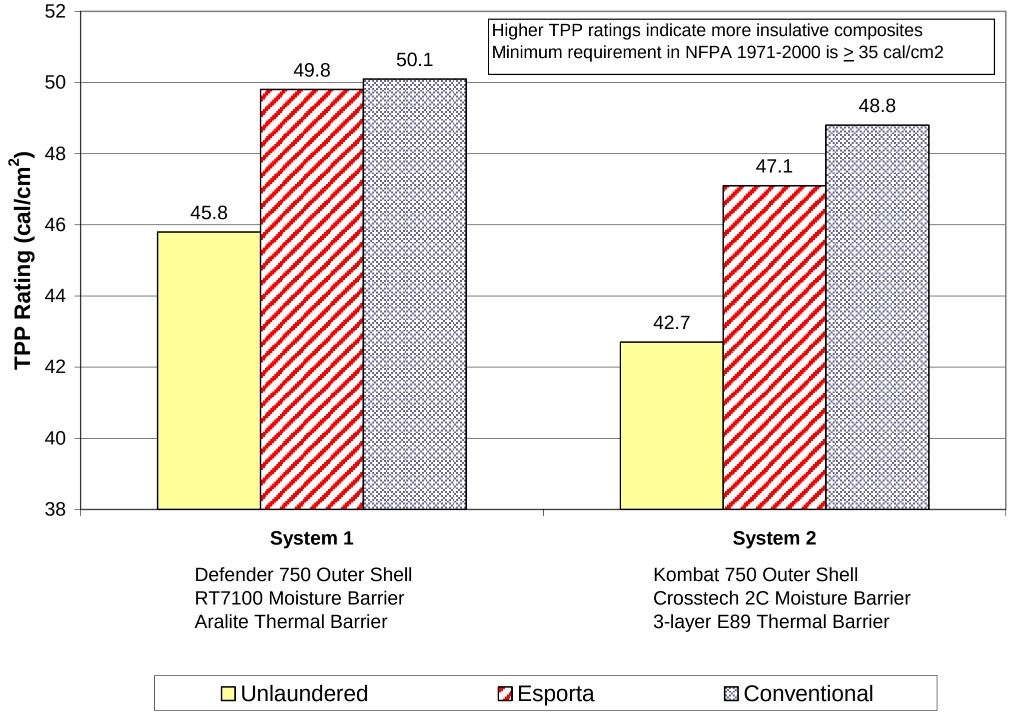

Figure 13 – Comparison of Laundering Process Effects on Composite TPP Ratings

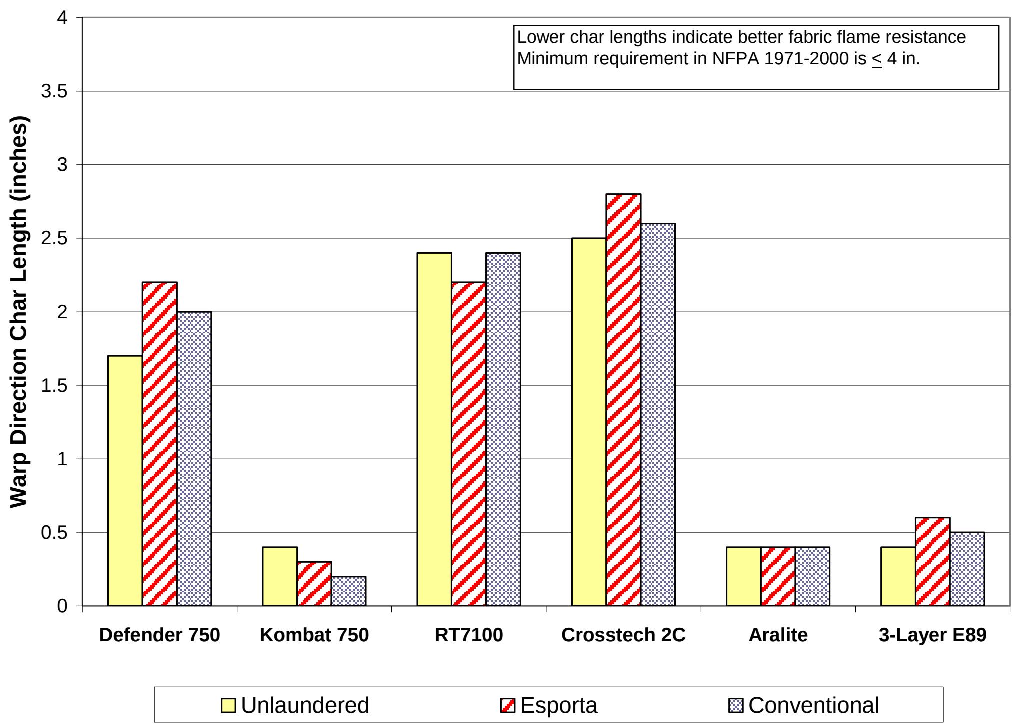

Figure 14 – Comparison of Laundering Process Effects on Fabric Char Length (Flame Resistance Testing, Warp Direction Only)

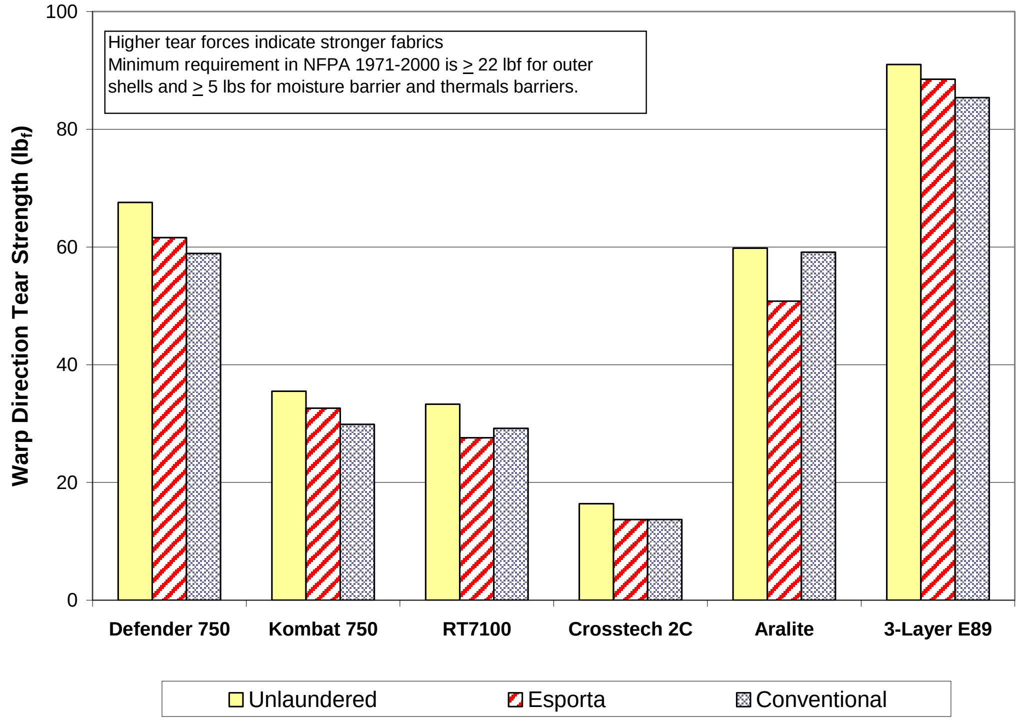

Figure 15 – Comparison of Laundering Process Effects on Fabric Tear Resistance (Trapezoidal Method, Warp Direction Only)

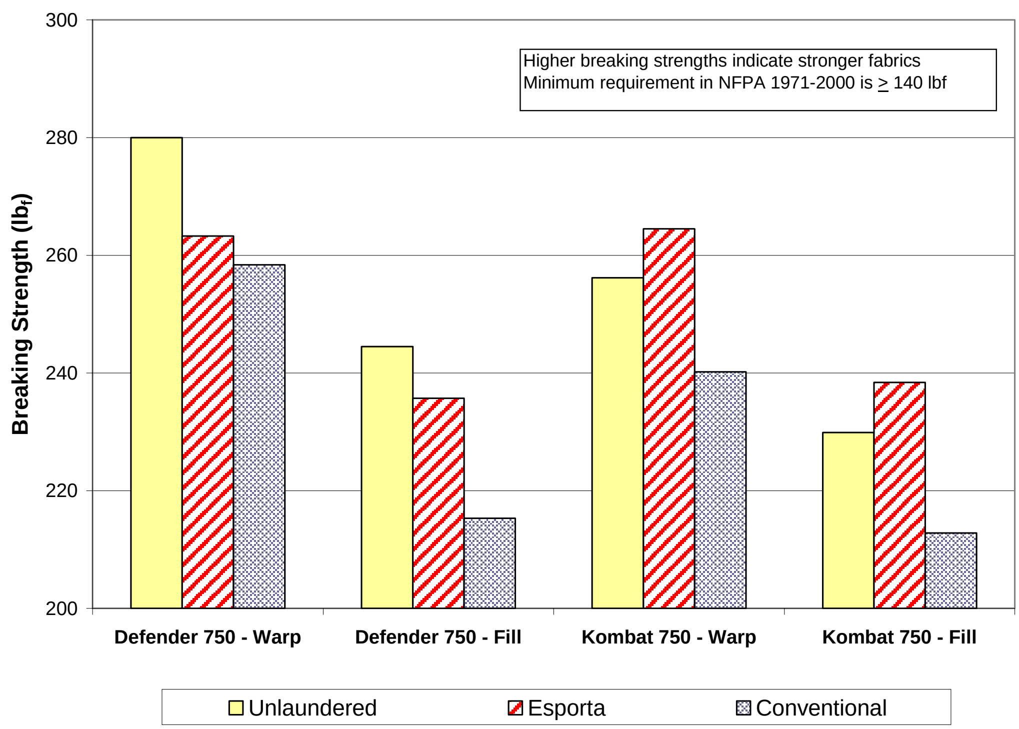

Figure 16 – Comparison of Laundering Process Effects on Outer Shell Fabric Breaking Strength (Grab Method)

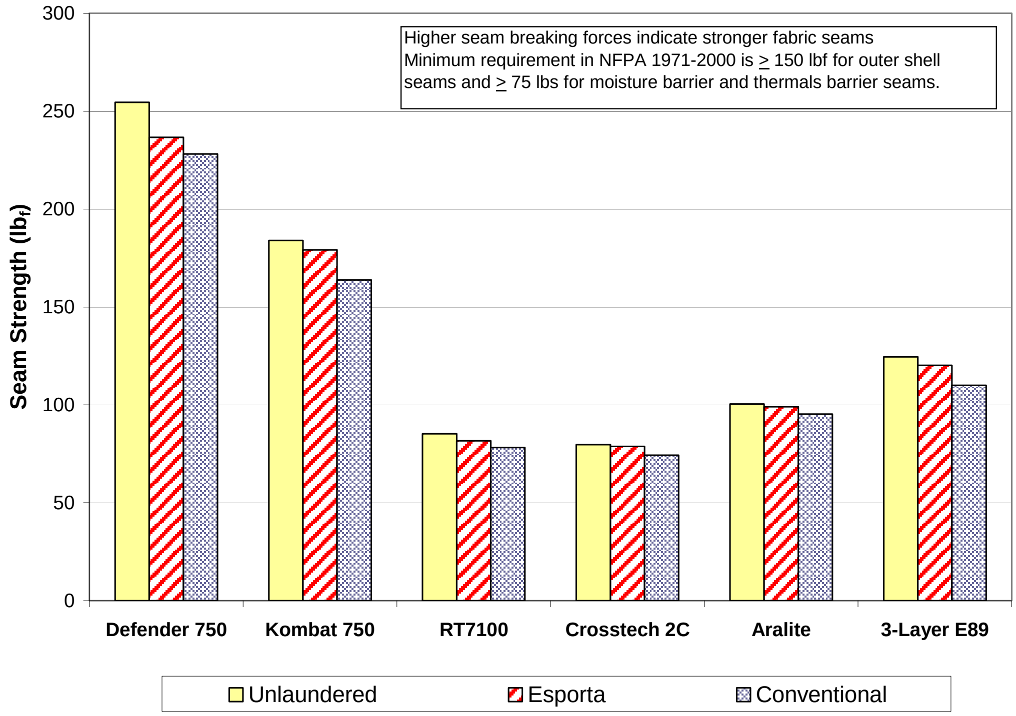

Figure 17 – Comparison of Laundering Process Effects on Fabric Seam Strength

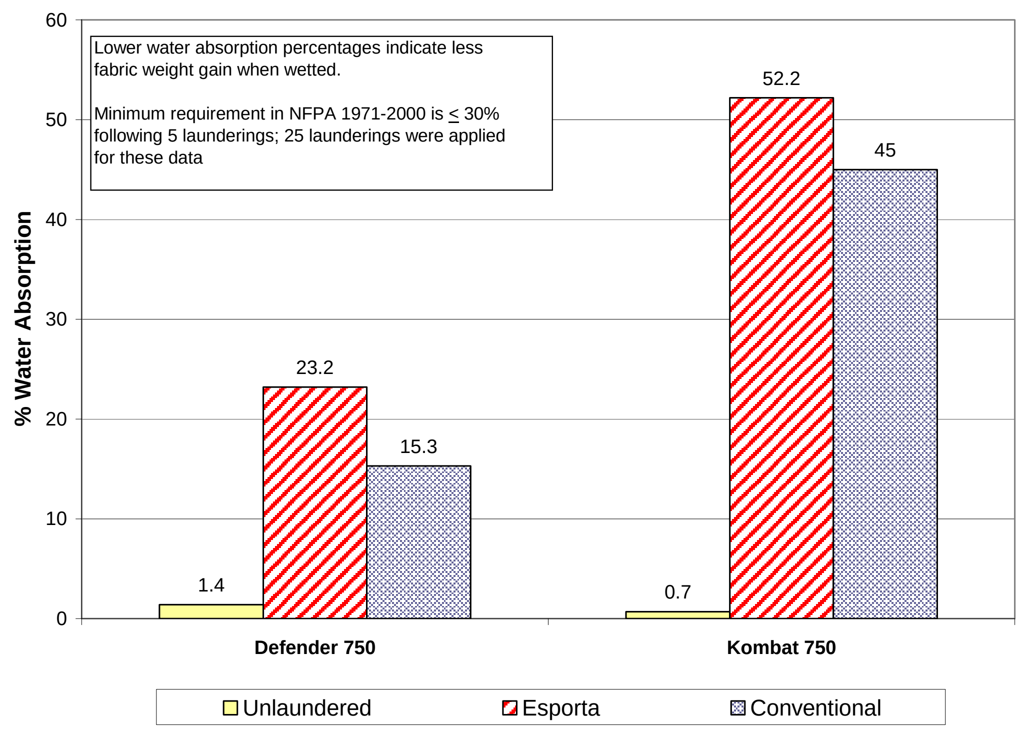

Figure 18 – Comparison of Laundering Process Effects on Outer Shell Fabric Water Absorption Resistance

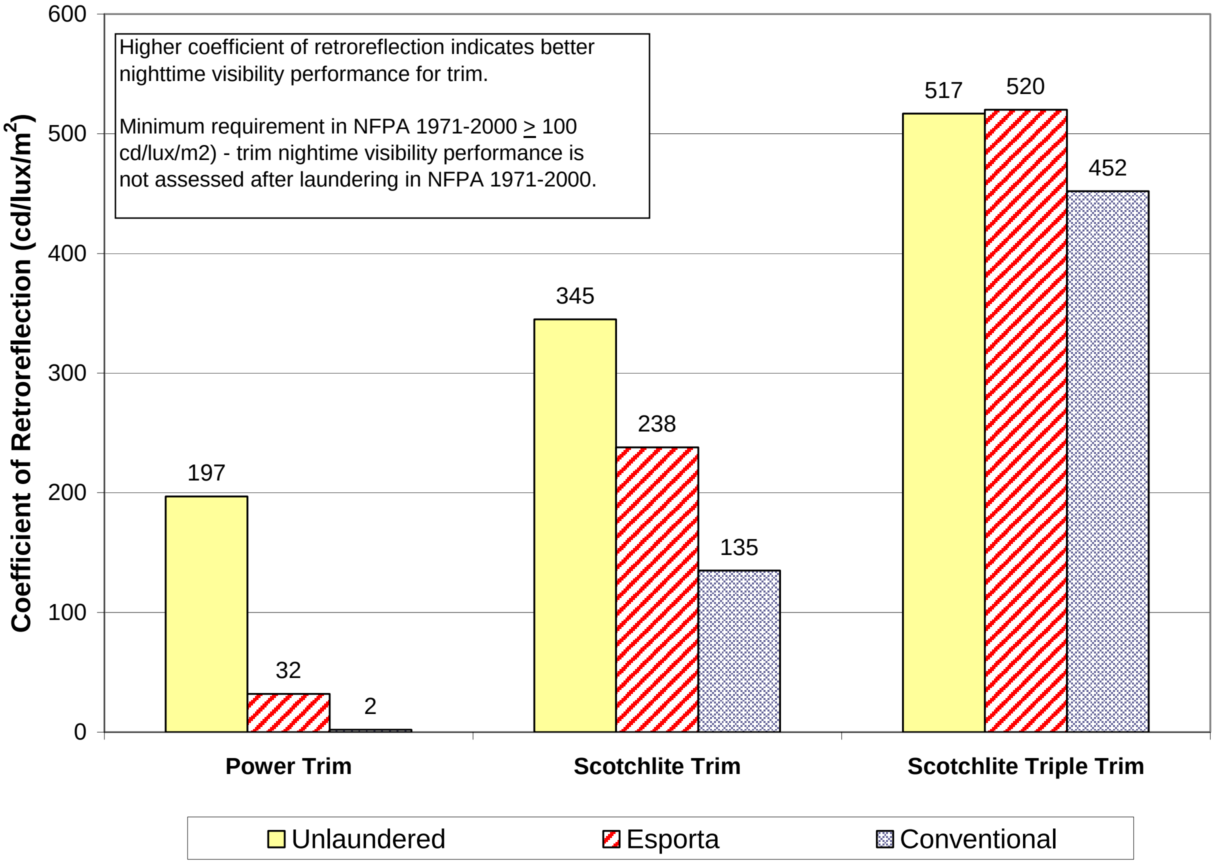

Figure 19 – Comparison of Laundering Effects on Trim Nighttime Visibility Performance

- There as no statistically significant differences noted in char length for the measurement of flame resistance for the outer shell, moisture barrier, and thermal barrier fabrics.

- As has been previously shown, tear resistance usually decreased with the application of 25 cycles of each laundering process. In many cases, there was a statistically significant difference between unlaundered and laundered fabrics for measured tear resistance but such differences were not always observed between laundering processes. In the majority of cases where there were differences between laundering processes, the Esporta laundering process showed a lower decrease in tear resistance.

- Breaking strength measurements of outer shell fabrics showed statistically significant differences between laundered and unlaundered fabrics and between laundering processes. The Esporta laundering process showed less effect on outer shell fabric breaking strength compared to the conventional laundering process.

- Seam strength measurements also showed statistically significant differences between laundering process and with unlaundered fabrics for outer shells, moisture barriers, and thermal barriers. Smaller decreases in seam breaking strength were observed for the Esporta laundering process. In one case, a normally compliant moisture barrier seam strength was reduced to below the acceptable value when subjected to the conventional laundering process.

- The largest changes in fabric performance were observed in evaluating outer shell fabrics for water absorption resistance. For one fabric, both laundering processes increased water absorption to beyond the maximum permitted level. Laundering effects were somewhat less with the conventional laundering process; however, both fabrics were dramatically affected by laundering. This evaluation points to the fact that laundering over multiple cycles will affect water absorption (as well liquid absorption and staining) resistance of fabrics. This is particularly true with the extreme case of 25 applied laundering cycles. Many manufacturers recommend that repellent finishes be reapplied after several laundering cycles.

- The penetration resistance of moisture barrier seams to both Fuel C (a surrogate chemical mixture for gasoline) and Bacteriophage Phi-X174 (a surrogate virus for HIV and Hepatitis) showed that the seams for the Crosstech moisture barrier remained intact without failure following 25 cycles of each laundering process. In the case of the RT7100 moisture barrier, failure was noted for two seam specimens against Fuel C and all three seam specimens for the bacteriophage following the conventional laundering process. There were no failures of any specimens for seams subjected to the Esporta laundering process.

- Three different trim products were evaluated for coefficient of retroreflection (nighttime visibility performance) following each laundering process. In the case of one trim product, the nighttime visibility performance of the product remained unaffected by the Esporta process, with some diminishment by the conventional laundering process. A second trim product showed declines in nighttime visibility performance with laundering but the effect of the Esporta laundering process was less. The third product show significant decreases in nighttime visibility performance with both laundering process with the conventional laundering process rendering this trim product essentially devoid of any nighttime visibility characteristics.

CONCLUSIONS AND RECOMMENDATIONS

Procedures have been developed which permit the evaluation of different laundering processes for the removal of both soiling and chemical contaminants. These procedures provide a means of quantitatively comparing the effectiveness for cleaning of firefighter protective clothing using specific contaminants and methods of analysis. When combined with the techniques established in NFPA 1851 for evaluating laundering process effects on clothing, a complete evaluation of a laundering process can be undertaken with respect it efficacy for cleaning and affecting firefighter protective clothing.

The use of a synthetic soil, originally intended for carpet cleaning evaluation, appears to offer a means by which firefighter protective clothing outer shell fabrics can be reproducibly soiled and then subjected to laundering. The specific method developed in this study by the University of Alberta creates a relatively extreme form of soiling that could be judged to be representative of an extreme soiling condition. Nevertheless, adjustments can be made to the synthetic soil mixture, method of soil application, and exposure time to produce other soiling conditions.

Different techniques for assessing the removal of soils offer a range of qualitative and quantitative evaluations. While a visual comparison is generally used in practice for determining when a fabric is clean, the application of Gray Scale ratings established by the American Association of Textile Chemists and Colorists (AATCC) provides a semi-quantitative method for providing a determining of soil removal. Decisions are needed as to whether the staining or color change scales should be used. It is also important to determine the fabric for comparison. Ideally, non-used but laundered fabric should be used for making these determinations. A truly quantitative method of evaluation involves the measurement of color and color changes. Different spectrophotometric measurements can be made to aid in quantifying how soiling is removed; however, more work is needed to determine the relationship of specific color change measurements with the degree of visual soiling.

The use of techniques established in the U.S. Fire Administration report, "Research, Testing and Analysis on the Decontamination of Firefighting Protective Clothing and Equipment," USFA Contract No. EME-96-CO-0505 (February 1999) provided a good starting point for examining the removal of chemical contaminants by laundering. Decontamination efficiency can be assessed by careful application of contaminants and analytical procedures. The extensive use of controls provides a needed basis for comparing contaminant removal. For this study, measurable decontamination efficiencies were obtained for the two outer shell fabrics and three chemicals; however, one chemical was probably too volatile (i.e., ethyl benzene) to provide an effective comparison between fabrics and laundering processes. Nevertheless, significant differences were observed for the other two chemicals (anthracene and dioctyl phthalate).

This study demonstrate the utility of the appendix information provided in NFPA 1851 for evaluating the impact of laundering processes on key firefighter protective clothing properties. The washing of surrogate clothing samples better mimics the way that clothing would be cleaned. While perhaps considered excessive, the extreme of 25 cycles of laundering will accentuate any effects of a laundering process and better demonstrate differences between two or more laundering processes.

A number of different laundering processes are available to the fire service for the care of the protective garments. While there are several generic procedures in place for use in the industry, the specific attributes of each process will affect process efficacy in cleaning, decontaminating, and causing wear/damage to clothing items. It is important for the fire service to have knowledge for the effectiveness of prospective laundering processes before choosing a specific approach since protective clothing often represents a significant investment for the department.

In this study, two different laundering processes were evaluated. The first process ("Esporta") represents a unique machine and chemical approach, which is designed to provide large throughput but in a manner where potential damage to the clothing is minimized while providing a comprehensive cleaning process. The second process ("conventional") was representative of a generic industrial laundering method and in fact was based on the garment conditioned specified in NFPA 1971, which set the minimum performance requirements for firefighter protective clothing.

Several different findings apply to the comparison to the two laundering processes considered in this study.

1. The Esporta laundering process showed better removal of soiling than the conventional laundering process based on both Gray Scale color/staining ratings and spectrophotometric measurements. While both processes failed to completely remove all soiling, there were observable differences for removal of the synthetic soil from both outer shell fabrics by the Esporta laundering process.

2. The Esporta laundering process demonstrated higher decontamination efficiencies compared to the conventional process for two semi-volatile chemicals (anthracene and dioctyl phthalate). These differences were significant for dioctyl phthalate on both outer shell fabrics and for anthracene on one of the outer shell fabrics. The removal of ethyl benzene was 100% for both laundering processes and both outer shell fabrics.

3. While a range of laundering process impacts were observed from both the Esporta and conventional laundering processes, in general the Esporta laundering process showed less reductions of protective performance as compared to the conventional laundering process. These findings were observed specifically for outer shell breaking strength, seam strength, liquid penetration resistance, viral (bloodborne pathogen) penetration resistance, and trim nighttime visibility performance. As expected, the effects on flame resistance were negligible in nearly all cases. Tear resistance results were mixed. Similar to other research, thermal protective performance improved for both processes. The only performance area where the conventional laundering process had less impact on clothing properties was for water absorption resistance. This result is not entirely unexpected because the better soiling and contaminant removal efficiencies for the Esporta laundering process would also have an impact on removing fabric repellent finishes. Another examination of the Esporta laundering process could be made with the reapplication of repellent finishes.

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APPENDIX A

SPECIFICATIONS FOR LAUNDERING PROCESS MACHINES