

Green Technologies and Sustainability in the Care and Maintenance of Protective Textiles

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Abstract—Protective textiles get soiled, stained and even worn during their use, which may not be usable after a certain period due to the loss of protective performance. They need regular cleaning and maintenance, which helps to extend the durability of the clothing, retains their useful properties and ensures that fresh clothing is ready to wear when needed. Generally, the cleaning processes used for various protective clothing include dry-cleaning (using solvents) or wet cleaning (using water). These cleaning processes can alter the fabric surface properties, dimensions, and physical, mechanical and performance properties. The technology of laundering and dry-cleaning has undergone several changes. Sustainable methods and products are available for faster, safer and improved cleaning of protective textiles. We performed a comprehensive and systematic review of green technologies and eco-friendly products for sustainable cleaning of protective textiles. Special emphasis is given on the care and maintenance procedures of protective textiles for protection from fire, bullets, chemical and other types of protective clothing.

Keywords—Sustainable cleaning, protective textiles, eco-friendly cleaning, ozone laundering, ultrasonic cleaning.

I. INTRODUCTION

APPAREL textiles are often rejected due to their change in appearance during wear, cleaning and storage [1]. However for protective clothing, protection, rather than appearance is the main requirement. The rejection of these garments is based on the amount of loss of the protection level or failure to meet the standard specification. Improper cleaning methods may not properly clean the items, which may affect the performance. For example, residual oil in a PPC worn by an oilfield worker may make the personal protective clothing (PPC) flammable, and thus, fail to meet the specifications. In several instances, the PPCs are rejected on the basis of visual assessment by an expert rather than performance evaluation, which involves destructive tests. This depends on the experience of the expert in interpretation of the change in the appearance of the PPC. This subjective assessment becomes more complex when the protective clothing consists of multiple layers such as firefighters' PPC. It is rather difficult to visually assess the internal layer(s) in a multi-layer firefighters' PPC. Furthermore, the cleaning methods adapted can change the comfort features of the clothing, which may become uncomfortable to wear for

extended periods [2], [3].

Appropriate care and maintenance of the PPC is important to the manufacturer and critical to the user. The safety of the user depends on the performance of the PPC to a great extent, which is affected by the care and maintenance process. In addition to proper cleaning, the care and maintenance procedure should remove the contaminants from the PPC that may affect the performance. This is essential to maintain the performance throughout the life of the PPC. Hence, to achieve this, the selection process for any PPC should consider the nature of contaminants and soiling including their care and maintenance procedure.

II. CARE AND MAINTENANCE OF PROTECTIVE CLOTHING

A. Cleaning of Firefighters' Protective Clothing

The useful life of a firefighter's protective clothing (FPC) is the time for which the FPC provides acceptable protection. Factors such as material, design, degree of exposure and intensity of flame, the maintenance and storage procedures affects the useful life of a FPC. The frequent use of the FPC makes it soiled with contaminants and body excretions. This in turn can reduce the protection needed leading to flame resistance failure. Hence, proper care and maintenance is needed for FPC to remove the contaminants. This section will deal with the care and maintenance of the FPC and its influence on the performance.

The FPC may consist of multiple layers with different functions. The washing protocols used for one layer may not be appropriate for the other layers. In some instances these layers are detachable, which means they can be washed separately. However, in an integrated FPC with multiple layers, appropriate protocols are necessary for effective cleaning.

The FPC may be either home or industrial laundered to successfully remove most types of flammable and non-flammable soils [4]. However, some types of soiling such as oily soils and heavy greases are hard to remove using home-use laundry detergents. The presence of soils that are flammable can compromise the flame resistance of the FPC. The thermal protection of the flame resistant clothing can be compromised by the presence of contaminants on the surface. Although the fabrics satisfies the requirements of flame protection as evaluated by the standard test, the presence of flammable contaminants in the uniform can burn easily, until consumed, leading to inadequate protection to the wearer. Hence, it is necessary to clean these flammable contaminants by appropriate methods prior to reuse. Laundering and dry-cleaning are the major maintenance procedures for FPC. It is

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to be emphasized that laundering affects the ageing process chemically and mechanically to a significant level.

The fabrics selected for the preparation of FPC should be able to withstand the protocols used for washing and dry-cleaning [4], [5]. In addition, the finishes applied should also withstand these processes. Washing detergent, the load, temperature and rinsing cycle should be carefully selected. The use of softeners, starch, bleach and other washing aids should be carefully considered as they can alter the performance of flame protection. Softeners and starches can deposit on the surface of the fabric altering the performance, whereas exposure to bleach can destroy the luminescence of the surface. Heavily soiled ensembles with particulate or abrasive soils should be pre-washed at 40°C initially, which will help to reduce abrasion in the wash wheel.

There is a gamut of detergents available that are designed to be used in a range of washing temperatures with no adverse effect on the FPC. The detergents and washing protocols should be carefully selected to clean the soiled garment thoroughly, even considering supplemental alkalinity and higher wash temperature. Light and dark colors in the load should be isolated as well as heavy and light soiled items. Loading the washer lower than the maximum capacity will provide the best results. The wash temperature is selected depending on the degree of soiling and nature of the material used in the FPC. Although, higher temperature is better for heavily soiled FPC, the care instructions and the compatibility with the washing chemical should be checked. In some instances, higher temperature may cause problems of shrinkage, color loss or change in appearance.

The majority of the detergents commercially available are alkaline with a pH value ranging from 9-13, which effectively remove the soil and other contaminants in the fabric. Higher temperature, longer cycle and supplemental alkalinity can be used to remove more aggressive soil and oil marks from FPC. The use of soft water is recommended for FPC [6], [7]. The use of soaps can form insoluble scrums with hard water, which gets deposited on the fabric. These scrums can adversely affect the flame protection of the FR clothing, as they are flammable. The protective clothing should be washed and dried inside out, which will help in retaining the properties of the outer layer. While laundering, the wash procedures and load sizes should be established to minimize redeposition and fabric abrasion. Short extract time can prevent wrinkle formation.

Residual alkalinity in the FPC can cause skin irritation and other problems [8]. Hence, it should be neutralized by the use of souring agents (weak acids) in the final rinse cycle to neutralize the alkalinity. Further, the washed load should be thoroughly rinsed to remove the residual washing chemicals. The combination of thorough treatment with souring agent and good rinsing will reduce the chances of skin irritations from higher pH. In addition, if there are residual chemicals in the FPC, the degree of flame protection provided by the FPC can be altered. Hence, to avoid this problem, the FPC can be tested for flame resistance as mentioned in ASTM D6413 (Standard test method for flame resistance of textiles (vertical test)). This

test is performed in an enclosed cabinet, where a controlled flame is exposed to cut edge of fabrics for 12 s. Five specimens are selected each for length and width direction, which are mounted in metallic frames covered on three sides. Parameters such as char length, afterglow and after flame are measured to describe the FR performance. ASTM 6413 is helpful to find out the performance of a single FPC or even a group of them after care producers. However, if the service history of the group differs, each garment should be tested separately.

The tumble drying conditions for FPC should also be carefully selected. Over drying in many instances leads to shrinkage, and hence should be avoided. Overloading of the tumble dryer can reduce the drying efficiency and result in improper drying. Removal of the FPCs while they are slightly damp (5-10% moisture) and hang drying will produce good results. The dried load should be instantly removed after the cycle is completed. Similarly, the pressing conditions should also be carefully selected to retain the appearance and protection performance of the FPC. There are several standards for the care and maintenance of FPC followed around the globe as described in TABLE I.

TABLE I
 VARIOUS STANDARDS FOR CARE AND MAINTENANCE OF FPC

Standard	Purpose
ASTM F1449	Standard guide for industrial laundering of flame, thermal and arc resistant clothing.
ASTM F2757	Standard guide for home laundering care and maintenance of flame, thermal and arc resistant clothing.
CEN/TR 14560:2003	Guidelines for selection, use, care and maintenance of protective clothing against heat and flame.
ISO/TR 2801:2007 (AS/NZS 2801:2008)	Clothing for protection against heat and flame-General recommendations for selection, care and use of protective clothing.
NFPA 1851	Standard on selection, care, and maintenance of protective ensembles for structural fire-fighting and proximity fire-fighting
NFPA 1855	Standard for selection, care, and maintenance of protective ensembles for technical rescue incidents.
NFPA 2112	Standard on flame-resistant garments for protection of industrial personnel against flash fire.
NFPA 2113	Standard on selection, care, use, and maintenance of flame-resistant garments for protection of industrial personnel against short-duration thermal exposures.

ISO: International Standards Organization, TR: Standardized document for information and transfer of knowledge, CEN: European Committee for Standardization, NFPA: National Fire Protection Association.

ASTM F1449 was developed in 1992 by ASTM international subcommittee F23.80, which was useful in providing care and maintenance information for industrial laundries. This standard describes garments soiled by flammable substances such as solids, solvents, oils and petrochemicals with flammability risk. If residues of these chemicals remain, it can help in increasing the flammability risks. These chemicals have strong odors, which help to detect the presence of residual chemical after laundering. Although this standard is helpful for industrial laundering, it provides limited information related to home laundering.

ASTM F2757 was developed by subcommittee F23.80 in 2009, which provides guidance for home laundering. This

standard is intended for the use of those who choose to select a home laundering program for flame, thermal and arc protective clothing. Although this standard does not recommend a home laundry procedure, it suggests to follow the garment manufacturer's care instructions. In addition, this standard lacks the information on other problems such as stain removal instructions; avoid the use of bleach, use of soft water for laundering, etc. The standard, along with the manufacturer's instructions, can serve the purpose for home laundering of FPC.

Several standards describe the test method to inspect the durability of the flame retardant (FR) finish subjected to repeat laundering. For example, AATCC 135 (Dimensional changes of fabrics after home laundering) most widely used American standard. This standard is referred in several other standards for FPC and other PPC such as ASTM F 1930, ASTM F1506, ASTM F2303, NFPA 70E. The protocol mentioned in AATCC 135 was unable to keep pace with the change in consumer choice. Hence, a set of guidelines was devised by AATCC and published as a separate monograph in the AATCC technical manual. Monograph M6 from AATCC (Standardization of home laundry test conditions) provides a set of guidelines for laundering and drying for many types of garment or fabric. ISO 6330 (Textiles - Domestic washing and drying procedures for textile testing) is the international standard similar to AATCC 135. This standard specifies protocols for fabrics, garments and other textiles that are home laundered and dried. There are 10 and 11 different washing procedures for front and top loaders, respectively. In drying, there are five processes ranging from line to tumble drying.

ISO 15797 specifies test protocols and equipment used for the evaluation of workwear of cotton and polyester/cotton blends in industrial laundering. This standard can also be used for FR clothing prepared from the blends of other natural and synthetic fiber blends. NFPA 2112 describes that the FR garments should be tested for the performance both before and after 100 cycles of washing as well as drying. The laundering protocol described in this standard is alkaline, which are used for heavily soiled PPCs. **Hata! Başvuru kaynağı bulunamadı.** II highlights the specifications for industrial laundry formula specified in NFPA 2112.

B. Cleaning of Body Armor

The ballistic panels of soft body armor become saturated with perspiration due to continual field use. The constituents of human perspiration are mainly water along with small quantities of organic compounds and inorganic salts. Human perspiration in the long-term can affect the properties of ballistic materials. The laundering of body armor is not recommended by the manufacturers, and even some standards specify not to clean them. For example, the National Institute of Justice (NIJ), who publishes standards for the testing of body armor, specifies not to clean the ballistic panels and coverings. However, the carriers can be washed and dried with conventional home laundering techniques. Hence, in many instances, wearers attempt to deodorize and clean the body armor by spraying the panels with odor neutralizer, cologne,

disinfecting sprays and/or wipe them with dilute solutions of detergent or bleach.

Studies have shown that not only the ageing reduces the ballistic performance, but also the method of care and maintenance affects it. NIJ standard provides guidelines and also evaluates the performance of body armors in use. The guidelines provided by NIJ can help to extend the useful life of the armor that may save someone's valuable life one day. These suggestions are discussed in the following section. Table II shows the instructions for cleaning body armor.

TABLE II
 DO'S AND DO NOT'S FOR CLEANING OF BODY ARMOR

Do's	Do not's
Dip dry the armor indoors	Machine wash or dry the armor as machine washing can alter the ballistic performance
Regularly inspect the armor for cuts, tears, and other damage to the carrier and ballistic elements	Bleach the armor or use products containing bleach for care and maintenance
Contact the manufacturer with any questions about care and maintenance of the armor	Use commercial laundering facilities as they may use harsh chemicals that can affect armor's protection performance
Manufacturer's instructions for care and maintenance of the armor should be followed. A person should be aware of the cleaning methods before doing it	Dry-clean the armor as dry-cleaning solvents can affect the armor's protection performance
When necessary hand wash the armor with a mild detergent in cold or warm water. Rinse it thoroughly to remove all traces of detergent.	Dry the armor outdoors as some ballistic fabrics degrade as a result of Ultraviolet (UV) exposure
	Attempt to repair the armor. Armor should be returned to the manufacturer for repairs or replacement

When washing of the whole body armors is allowed (such as combat clothing used for Tier 1 and UBACS (Under Body Armor Combat Shirt) are routinely laundered), it is important to closely follow the care instructions provided by the manufacturer as there is a strong impact of the care process and chemicals on the performance. Appropriate methods of cleaning and storing can help to maximize its service life and effectiveness of protection. It is always very important that the users become better educated on how their vests should be cared, stored and maintained. It is an investment that can save an officer's life.

Laundering of body armors negatively affects the physical and mechanical properties like the apparel fabrics. The effect of multiple washing and drying cycles on the fragment protection was analyzed by Helliker et al. [9]. Woven para-aramid (a), para-aramid felt (b), hydro-entangled UHMWPE (ultra-high molecular weight poly ethylene) felt (c) and single jersey knit silk (d) was used in this study. It was observed that the ballistic performance (measured using 0.24 g FSP) of fabric (c) and (d) was not affected by the laundering up to 27 laundering cycles. However, both the fabric (a) and (b) showed improved ballistic performance against 0.24 g FSP after nine laundering cycles. Furthermore, the reason for the increase in the performance was uncertain and it was assumed that the increase in friction between fibers/yarns due to the removal of the lubricants used in knitting/weaving or due to the surface peeling of the fibers might have resulted in the

increased value.

This study also established significant change in the physical properties due to laundering. Shrinkage was observed in all the fabrics, which lead to the increase in the thickness of the samples. The increase in the thickness did not change the ballistic performance of the fabrics. However, it might have changed the thermal resistance of the garments and resulted in change in the appearance. No significant changes in the mass of the fabrics were observed, which indicated no loss of fiber during laundering. Ballistic protective clothing comprising of felts were more severely affected by laundering than the woven or knitted fabrics examined in the study.

Fibers such as silk and para-aramid are degraded by laundering due to surface peeling of fibers, which may lead to loss in tenacity of yarns and fabrics. The surface peeling of fibers may increase the friction between the yarns, which can increase the ballistic performance of the fabrics after laundering. Other possible causes of change in the ballistic performance can be attributed to the removal of the lubricants from the fabric that was used during weaving or knitting. It has been earlier shown that the scoured fabric has improved ballistic performance to identical fabric in the loom state due to the removal of the lubricants.

The body armor can be designed by placing the protective layer inside a washable and breathable carrier. The carrier is generally made from cotton or other absorbent material to provide wicking of the sweat. The carrier can help in improved breathability in addition to the ease of care and maintenance. The carrier can be separated from the armor panel for care and maintenance. However, the armor may become bulky without significant contribution of protection by the barrier [10].

The effects of various cleaning chemicals such as odor neutralizer, liquid detergent and chlorine bleach; and perspiration on the tensile, chemical and surface morphological properties of different ballistic materials (aramid yarns and fabrics, UHMWPE yarn, and PBO yarn) were investigated by Chin et al. [11]. It was observed that the tensile properties of the aramid and PBO materials decreased after exposure to plain water, artificial perspiration, detergent, odor neutralizer, and chlorine bleach. The tensile strength of UHMWPE was decreased only in chlorine bleach. Chlorine bleach resulted in a significant decrease in the tensile strength for all the materials compared to plain water. Chlorine bleach caused physical changes in the fiber surfaces, which may have caused the damage to the fibers.

Significant chemical changes initiated by strong oxidizers in the bleach were observed in the FTIR results. Aramids and PBO showed hydrolytic degradation, whereas UHMWPE showed oxidative degradation, which resulted in the change in fiber tensile properties. It was concluded that exposure to chlorine bleach over a period of time could damage the soft body armor of aramid, UHMWPE and PBO fibers significantly. Hence, chlorine bleach should be avoided in the routine care and cleaning of armor. Although, additional damage was not observed on the ballistic fibers exposed to aqueous-based cleaning and artificial perspiration beyond that

of water alone, it should still be noted that water can degrade the mechanical properties of aramid and PBO fibers in long-term. Hence, the use of water and/or any aqueous-based products should be avoided or minimized in the care of soft body armor.

C. Cleaning of Chemical Protective Clothing

The amount of research on the cleaning of chemical protective clothing is limited. The chemical protective clothing can be contaminated during the application of the toxic chemicals, which may be absorbed by the fabrics. Wearing of the contaminated clothing can result in higher levels of exposure to chemicals compared to clean clothing [7], [12]. The amount of soiling depends on the chemical nature of the textile fiber, chemical treatments of the fabric and type of chemical (i.e. whether oil or water based). Penetration of soil, entrapment of soil in the fiber structure, and/or in the spaces of fibers worn by mechanical wear during laundering or during use, and chemical reaction of soil with fiber and finish can cause difficulty in soil removal.

Soiling of chemical protective clothing can occur when the textile is worn during chemical application or during laundering by cross-contamination. During laundering the chemicals can be transferred from a soiled cloth via the washing solution to another. It can also occur by the redeposition of soil removed from the area of soiling into the washing medium, and thus to all areas of that cloth including the other clothes [13]. Some clothing retain the soil residue in laundered fabrics regardless of temperatures, detergent type, additives, pre-rinse or wash cycle, pre-wash treatment, fiber content, textile finish and type of fabric.

In some instances, pre-rinsing can help in better removal of chemicals from the clothing. Pre-rinsing can involve additional cycle in the washer, soaking in a container prior to the wash cycle or rinsing under a stream of running water. Several researches have shown that pre-rinsing helped in the cleaning efficiency of the chemical contaminated clothing.

The concentration of the laundering chemicals affects the contaminant removal during laundering. It was observed that the degree of difficulty in removal of the chemicals increases with the increase in the concentration of the chemicals. The formulation and laundering process can also affect the removal process. Encapsulated and wettable powder formulations were easy to remove than the emulsifiable concentrate.

Depending on the nature of the chemicals and the fabric type, one washing cycle may not be sufficient to remove the chemicals. Hence, multiple washing cycles are needed to effectively remove the chemicals. The time frame between the contamination and washing also affects the efficiency of cleaning. Immediate washing of the contaminated clothing can significantly improve the chemical removal. The storage of the clothing for longer period can help the chemical to be strongly adhered to the substrate, hence making the removal difficult.

It is essential to remove the contaminants present on the surface or inside the matrix, or on both before the reuse. The chemical PPC can be cleaned by the combined process of pre-

soaking, air drying, washing and drying at elevated temperature. The use of appropriate chemicals is also essential for this purpose. The efficiency of decontamination can be calculated using the following formula:

$$\text{Decontamination (\%)} = (\text{weight loss/weight gain}) \times 100$$

Where, Weight gain = weight of the exposed specimen – weight of the virgin specimen. Weight loss = weight of the exposed specimen before decontamination – weight of the exposed specimen after decontamination.

D. Cleaning of Other Protective Clothing

Surgical gowns or scrubs become contaminated with microorganisms during wear, and therefore, needs effective cleaning before being used again. After daily use or whenever the gowns become visibly soiled or wet by blood, body fluid or sweat, reusable surgical attire should be laundered in a facility-approved and monitored laundry. However, laundering of surgical attire in home laundries is not recommended as it can result in the potential spread of contamination in the home environment. Surgical gowns simply worn in a medical environment are more likely to be soiled by perspiration, body oils or material handling during the performing of other duties [14]. Soiled attires are not classified as contaminated unless the garments have come in contact with blood or other potentially infectious materials. Contaminated scrubs under no circumstances should be laundered in a domestic environment. However, all kinds of soiled attires can be laundered in a domestic environment.

In several countries, the rule states that “If the surgical gown (owned by the hospital or not) worn by the employee gets contaminated, the employer is responsible for laundering it” [15]. In addition, some of the hospitals specify the policy and procedures for launder-at-home situations. There are four factors affecting the degree of decontamination of surgical gowns such as [16]:

1. The action of the washing chemicals and other aids that are used,
2. Washing temperature,
3. The dilution (repeated suds and rinse bath), and
4. The duration of the wash cycle.

The majority of scrubs are polyester/cotton blends with the labels specifying “no chlorine bleach” as the bleach may affect the color of the scrub. Scrubs need to be treated with disinfectants to kill the bacteria. Often, the commercial disinfectants contain bleaches, which is a concern for the scrubs to fade in color due to the bleaching action. The disinfectant’s capacity to kill the bacteria depends on the amount of bleach in the disinfectant’s composition.

Many detergents are commercially available for domestic use; however, these may not be appropriate for use as laundry sanitizers for hospitals. The laundry sanitizers for hospital outfits must demonstrate their efficacy against a representative gram-positive bacterium (e.g. *Staphylococcus aureus*) and gram-negative bacterium (e.g. *Klebsiella pneumoniae*). In some cases, additional tests may need to be performed using other

microorganisms than the two mentioned here. In all the cases, the sanitizer should be capable to “kill 99.9% of bacteria” [17].

Doty and Easter [18] investigated the effects of care and maintenance of various technical textiles by washing and drying. The technical textiles were antimicrobial, stain repellent, stain release, moisture management and ultraviolet (UV) protection materials. Garments were subjected to repeated laundering and drying cycles in a single load. The performance of garments was evaluated prior to and after laundering (maximum of 20 cycles).

The results showed that that laundering and drying of various technical textiles in one load did not have a significant impact on the performance. Although they were subjected to 20 washing and drying cycles, their chemical structure was not affected. It was assumed that mixing of various functional textiles during washing and drying can affect the performance of each other within the first few cycles. However, this assumption was not accurate, as any changes in the performance were not observed after washing and drying. In addition, no garment acquired functional characteristics of other garments in the load. However, there was a slight change to the appearance and dimensional stability.

The FR high visibility garments must be laundered separately in water lower than 60°C or dry-cleaned either with Perc or petroleum solvent [19]. The use of natural soap, hard water, bleaches, long washing cycle, over drying, high wash temperature, starch, fabric softener and other additives should be avoided. The use of bleach can damage the clothing, whereas starch and softener may reduce the performance due to its presence in the fabric surface. High water levels, soft water, short extract time, detergent with high surfactant and low alkalinity, and thorough cold water rinsing and permanent press/low setting ironing are suitable for these protective clothing.

Heavily soiled garments with abrasive soils can be washed at 40°C at the beginning of the cycle to reduce the abrasion. The washing load and chemicals should be established to avoid fabric abrasion and redeposition of soil. Short extract time can help to avoid wrinkles, whereas tunnel finishing or ironing at short washing cycle can improve the appearance. The clothing can be repaired for minor faults, not affecting the integrity of the garment, by using similar materials either by heat sealing or sewing on patches.

The FR high visibility rainwear should be hand washed or machine washed using cold water and gentle cycle to retain the FR properties and the hi-visibility. Abrasive cleaners or solvents should be avoided. These items should be kept away from bleaches, softeners and dry-cleaning. They should be hung dried and not ironed.

The protective clothing for molten metal can be laundered (either home or industrial equipment at low washing and drying temperature) or dry-cleaned. The use of hard water should be avoided as the metals salts in hard water can form insoluble deposits on the fabric surface, which can affect the protection level. Excessive deposits may serve as a fuel to a fire if the garments are exposed to an ignition source. Tunnel

finishing is not suitable for these garments as it may result in excessive shrinkage.

As a wide range of equipment and chemicals are used for cleaning, these items should be tested by in-house laundering for any adverse effects. Garments soiled heavily or with splash metal should be cleaned by dry-cleaning for higher efficiency. The use of natural soap, long washing cycle, high wash temperature, starch and bleaches should be avoided. The use of bleach can damage the clothing, whereas starch may reduce the performance due to its presence in the fabric surface. High water levels, detergent with high surfactant and low alkalinity, and thorough cold water rinsing are suitable for these protective clothing. Hydro extraction should be done at low speed only for short duration.

While laundering at home, use home laundry detergent. Avoid tallow soap, starch and bleaches. Select permanent press or gentle cycle with cold or warm water (maximum temperature 60°C). Use low/delicate cycle in tumble drying and remove promptly.

Conditioning, tunnel finishing (if used) and pressing temperature should not exceed 120°C. Perc or petroleum solvent should be used for dry-cleaning. The residual dry-cleaning solvent or washing chemicals should be removed. The clothing can be repaired for minor faults not affecting the integrity of the garment using similar materials either by heat sealing or sewing on patches.

The protective clothing used for Sun/UV protection is prepared from the blends of cellulosic fibers and synthetics. Laundering of new clothes can improve their protection level, especially clothes made of natural fibers. This might be due to the shrinkage reducing the gaps in the structure. As the clothes become older, they may offer decreased protection due to regular care. After the first wash, the washing reduces the SPF to a larger extent compared to the subsequent washes. Hence, these clothes can be treated with UV absorbers to absorb more UV radiation.

When using sun-cream or lotions on the body, these should be applied 15-25 minutes prior to putting the UV clothing to avoid staining or discoloration of the fabric. The UV protective clothing should be washed soon after each wear. If they cannot be washed, at least a rinse in cool water is necessary. When using a washing machine, cold water and a gentle washing cycle using mild soap/detergent can provide good results. These clothing should not be wrung, rather lay flat to dry. The garments can be rolled in a dry, clean towel, to absorb excess water, which can speed up the drying process. They should not be bleached, dry-cleaned or ironed, and should be stored when they are completely dry.

Cold weather protective clothing needs special care during the care and maintenance as they contain multiple layers of different materials [20]. The appropriate care procedure for one layer may be harmful and/or ineffective for other layers. The situation is aggravated if the cold weather clothing is highly contaminated, which is often the case in some sectors. Heavily soiled or contaminated cold weather clothing cannot be properly cleaned in cold water, especially for oil-based dirt. In oil based soiling, the oils are not sufficiently softened to be

removed by the roll-up mechanism. Enzymes that are effective in cold water are an important additive to breakdown other insoluble dirt residues.

While cleaning the cold weather protective clothing, the garments should be checked for any mechanical damage and repaired. The dirt and stains should be pretreated before washing or dry-cleaning to facilitate their removal. Cold weather protective clothing can be wet cleaned at a commercial laundry instead of dry-cleaning with organic solvents. Professional wet cleaners use wet cleaning equipment with water and they operate in tandem with their dry-cleaning machines. Wet-cleaning of cold weather clothing in a commercial laundry is more appropriate than the use of organic solvents. The wet cleaning can be done on very dirty clothing, rain wear and items with microporous structures.

The outer layer of a cold weather garment is soiled by air pollutants (carbon black, acidic gases), body excretions and direct contact with dirt or food residues; among these, about 40% are water soluble and 10% are solvent soluble. Various textiles were grouped by Wentz [21] according to their preferred method of cleaning in to two categories, aqueous and non-aqueous cleaning. Cold weather items such as overcoats, parkas, raincoats, sweaters, windbreakers, blankets and sleeping bags) were nearest to the aqueous end of the scale. After wet cleaning, the garments should be thoroughly rinsed for detergent residues, which are not desired.

In some occupations, the contamination of cold weather work clothing is inevitable. For example, the workers in many parts of the oil and gas sectors working in cold climates. Contaminants such as dirt and greases accumulate in the cold PPC, which reduce the effectiveness of its protection. Hence, outer garments such as parkas need to be cleaned before the contaminants settle into the fabric, which makes it difficult to remove. Members of the US military are advised about the difficulty of removing grease and oily contaminants from cold weather parkas (i.e. windproof jackets). These contaminants are hard to remove as high heat is needed to remove these stains, which in turn may damage the properties of material. In addition, many outer garments prepared from synthetics are also hard to clean at high temperature.

Aeration is suitable approach for the removal of some type of contaminants. Dry-cleaning and professional wet cleaning are not always accessible to laborers working in remote areas. In their research, Crown et al. [22] aimed at establishing care procedures for workers at remote locations, which are close to domestic laundry conditions. The use of laundry pre-treatments (with domestic pre-laundry sprays or in a degreaser) was necessary to remove motor oil from aramid fabrics. As the contaminants or number of laundry cycles increases, the level of difficulty increases to remove the contaminants.

The outer layer of the cold weather PPC with durable water repellent (DWR) finish (silicone or fluoropolymer) may be removed due to multiple cleaning or may become ineffective due to dirt, detergent residues or fabric fluoropolymer softeners. Hence, in order to get back the required protection it is necessary to reapply the DWR finish, which is available in

sports outlets or outdoor clothing retailers.

The cold weather apparel prepared using Gore-Tex breathable water repellent membrane should be cleaned in accordance with their instructions for safe cleaning. For grease or oil-based stains, a pre-wash spray before cleaning can provide improved results. Warm machine washing (40°C) using liquid or powder detergent without bleach or softener is ideal for cleaning. To remove the traces of detergent residue, they should be thoroughly rinsed. Although commercial dry-cleaning can be used for Gore-Tex membrane, special care should be taken by the dry-cleaner to avoid any damage. The microporous structure of the breathable membrane may be clogged with dry-cleaning solvent as it contains surfactants and other additives. They should be treated with an extra rinse cycle with fresh solvent.

III. ECO-FRIENDLY AND SUSTAINABLE CLEANING PROCESSES AND MATERIALS

Green cleaning refers to the use of cleaning products and methods, which are eco-friendly to preserve human health and environmental quality. Green cleaning products and techniques avoid the use of toxic chemicals, some of which emit volatile organic compounds negatively affecting the respiratory, dermatological and other health conditions in addition to the environmental pollution [23]. Consumers are also becoming aware and emphasizing the use of eco-friendly cleaning products.

Conventional detergents can contain toxic ingredients that are harmful to the ecosystem, human being and the environment [24], [25]. For example phosphates in conventional laundry soaps can cause algal blooms, which negatively affect ecosystems and marine life [26]. Hence, consumers should always select eco-friendly detergents. There are many commercial detergents available with labels indicating various eco-labels such as: a product is readily biodegradable; phosphate-free; and made from plant- and vegetable-based ingredients, which can help consumers to select an eco-friendly chemical. These detergents or soaps are gentler on skin and to the cloth.

Similarly, soaps are available, which are made from certain tree seeds or oils that are easily biodegradable. A cup of white vinegar can be added to the washer during the rinse cycle, which acts like a softener. Vinegar naturally balances the pH of soap, leaving the clothes soft and free of chemical residue.

Various agencies are also focusing on the use of eco-friendly methods and products for laundering. For example, United States Environmental Protection Agency's (EPA) "Design for the Environment Program" labels products that satisfy EPA's criteria for chemicals. These products can contain the "Design for the Environment (DfE)" label. Generally, products labeled as 'low' or 'zero' Volatile Organic Compounds (VOCs) are safer for human health as well as for the environment. The following section describes the steps the domestic consumers can follow to make the cleaning as green cleaning.

1. Ozone Laundering

Ozone laundering systems have recently been shown to be successful in commercial installations because of reduction in the use of energy, water and chemicals. Ozone laundering is eco-friendly and it has been proven that fabric lasts longer thereby reducing replacement costs. Ozone enhances the effectiveness of the chemicals by supplying oxygen to the laundry water, thus reducing the need for high temperature washing with lower amount of laundry chemicals [27], [28]. Ambient to warm water temperature is needed for ozone laundering. High temperature dissipates ozone prematurely, negating its power; whereas, low temperature has a higher saturation level of ozone providing better cleaning efficiency.

As ozone laundering systems normally require fewer rinse steps, water usage is reduced by an estimated 30-45%. These systems recover most of the water used, so the reductions in water usage may be as high as 70-75%. Ozone oxidizes the soiling in linen, making it easier to remove from the washed water. It can also reduce the need for harsh, high pH traditional chemicals for same cleaning effectiveness. Ozone reduces the quantity of chemical usage. The cost of chemicals is typically reduced by a minimum of 10%, but in certain cases the cost can be reduced by 50% [29]. Heavily soiled loads consisting of oily rags, food and beverage can be washed effectively with ozone in warm temperature water to get the quality required. Typical reductions of energy are in the range of 80-90% for most laundries. The resultant savings claimed by laundries range from 5-30%.

New chemical formulations specially developed for low temperature ozone laundering are commercially available. Compared to the standard formulations for washing, these new chemicals greatly enhance the cleaning efficiency. Ozone in water solution performs some of the functions of chlorine bleach; it assists in water softening by helping to remove cations such as calcium and magnesium from the water.

Ozone laundering improves the life and quality of textiles because it enables a shorter cycle time and lower temperature. The wash cycles can be reduced by 10-40% per load as the wash and rinse cycles are reduced. A reduction in the amount of chemicals used also helps to improve the fabric life. Generally, the cost of linen replacement is much higher than water, chemical and energy costs. Ozone laundering can provide significant savings in this area. In addition, the effluent will contain lower levels of biochemical and chemical oxygen demand (BOD and COD) because ozone oxidizes bacteria, other micro-organisms and some dissolved organic compounds. The reduced washing and rinsing time means the laundry equipment is used more efficiently and the total staff hours per load is reduced. Furthermore, ozone is not dangerous to humans in the concentrations typical for ozone laundries compared to other chemicals.

2. Ultrasonic Cleaning

Water is used for many laundering activities due to its high solvency for many substances in addition to the demonstrated occupational and environmental safety. However, the cleaning of hydrophobic contaminants is difficult to remove by water

from hydrophobic surfaces such as polyester. The use of detergents and mechanical action during washing can damage the fabric. The use of ultrasound, another type of mechanical action, for cleaning of hard surfaces has been reported to be effective for textiles as well [30]-[34]. The application of ultrasonic energy can prevent the fabric damage that occurs in the conventional mechanical washers. The cleaning by ultrasound depends on the rapid formation and violent collapse of bubbles or cavities in cleaning liquids [35]. Ultrasonic can be applied to textile laundering and dry-cleaning operations.

The use of ultrasound cleaning is gentler to the fabric compared to the mechanical agitation the laundering machine. The aggressive flowing and rotational agitations of wash bath and the deformations of the fabric and friction between the fabric surfaces do not take place in ultrasonic energy. Furthermore, ultrasound can remove the soils deposited in the fabric even at low liquor ratio and in a shorter cycle. This can lead to both water and energy saving. In addition, high-frequency ultrasound can remove stains on fabrics via generation of active species in liquid. However, ultrasound is generally not suitable for regular cleaning of soft and flexible materials such as textiles.

The mechanism of cleaning by ultrasonic is significantly different from conventional home laundering. In home laundering by machine or even hand washing, rubbing to the fiber surface occurs by aggressive stirring, agitation and plunging actions in the bath accompanied by chemicals. The transfer of the stains from the fiber surface into the bath is achieved with the help of detergents. However, ultrasonic laundering is a more gentle process, where the fabrics lie almost stationary in the ultrasonic bath. The acoustic cavitation produces a micro level of high-speed liquid movement accompanied by a vibration at the liquid-fabric interface through which the stains are removed. In theory, the deformation and damage to the fibers and yarns in a fabric induced by ultrasonic agitation may be much less than that of mechanical agitation.

Conventional laundering of silk items can lead to crease and deformation. The fabric rubbing during the laundering process cause fiber fractures in the form of fibrillation and degradation [36]. The appearance and wear endurance of silk garments are affected by this, which lead to considerable inconvenience in everyday use. As silk fabric can change in size and lose its tactile property or feel, the durable press finishing that is effective in improving the crease resistance to laundering, cannot be applied to silk. Dry-cleaning of silk fabric is relatively ineffective in removing water-soluble stains and it is expensive. Ultrasonic laundering was found to perform much better in removing common stains from silk fabrics, while the fabric appearance and dimensions was maintained compared to the machine laundering [37]. In addition, there was less fiber damage by ultrasonic laundering to the fabric. This research showed that the introduction of ultrasonic laundering could produce a significant benefit for silk fabrics. However, ultrasonic agitation caused a slightly higher color fading than the mechanical agitation. The K/S value of the fabric

laundered by ultrasonic agitation after 15 laundering cycles was only 2.7% lower than the fabric laundered by washing machine, and the difference was not significant.

Blood stains from polyester/cotton-based medical surgery gowns [33] and soils from polyester and cotton fabrics can be efficiently removed by ultrasonic laundering in shorter time and at lower bath ratio [38]. Home laundering of wool fabrics generally leads to felting shrinkage. However, ultrasonic laundering of woolen clothing can reduce fabric felting whilst achieving good stain removal compared with hand washing [30], [31]. The repeated ultrasound washing cycles did not affect the color and the tensile strength of the fabric [39]. Millions of bubbles or cavities are created by the ultrasonic energy with very high frequency into the liquid, which constantly strike at the target material surface and as a result, removes the dirt off textile materials. The most important parameter in the mechanism of ultrasound cleaning is the power of ultrasonic cavitation in liquids. Ultrasonic use work better for the stain removal from a stained fabric. A higher velocity of the laundering solution at the fiber surface is achieved by ultrasonic irradiation. This increased velocity improves the mechanical removal of the stain from the surface of the fiber.

Cleaning by ultrasonic has many advantages over the conventional laundering process such as (a) superior cleaning properties, (b) reduction in cycle time, (d) reduced energy consumption, (e) less chemical and (f) less mechanical damage to the clothing due to less fiber migrations. In spite of the above mentioned advantages, there are several disadvantages associated with the ultrasonic cleaning of textiles, which are mentioned below:

1. It is difficult to achieve a homogeneous distribution of the acoustic field in the whole washing load, which may lead to irregular washing. There will be some areas of low acoustic energy, which can result in improper cleaning. However, this problem can be overcome by moving the washing load continuously, so that all the clothes pass through the areas of high ultrasonic intensity.
2. For the effectiveness of cleaning, the wash load has to be exposed to the ultrasonic field in such a way that there is the continuous production of "strong transient cavitation" on the fabric surface. The collective cavitation of a large number of bubbles in the gassy liquid is needed for good cleaning. However, the softness of the fabric facilitates cavitation to produce small erosion effect while its reticulate structure favors the formation of layers of big bubbles that obstruct wave penetration [40].
3. The commercial development of ultrasonic washing machines for domestic laundering is difficult due to the difficulties in the designing of a suitable washing machine.

i. Sustainable Chemicals for Laundering

There are several companies producing environmentally friendly formulations for cleaning, which are easy to use, effective and productive in cleaning performance, and save resources and water. Many of them use detergents of non-

petrochemical origin or substances which have been produced through genetic engineering [41], [42]. The use of washing substances closest to nature (such as soap) can guarantee a simple return into the natural cycle. Natural products such as baking soda, lemon juice, salts, pure soaps and palm oil can be used to make the products eco-friendly. Various companies are using these products to prepare formulations that include ecological bleaching agent and stain remover, ecological washing powder, ecological laundry detergent, wool and delicate laundry detergent, soap bars and disinfectant. Consumers need to be aware of these products to make the care and maintenance of clothes eco-friendly.

ii. Sustainable Chemicals for Dry-Cleaning

There are some chemical listed as eco-friendly and are being used in the dry-cleaning of clothing items as discussed in the following section.

1. **Hydrocarbon:** Hydrocarbon based solvents such as Chevron Philips' EcoSoly or Exxon-Mobil's DF-2000 can be used in standard dry-cleaning. These petroleum based solvents are less aggressive than perc, and hence, need a higher temperature and longer cycle during dry-cleaning. Thus, some heat sensitive materials such as wool or acrylic may be adversely affected by the dry-cleaning. Longer cycle time indicates more mechanical action on the fabric. Unlike perc, these solvents are safe to use with beads, plastic buttons and sequins. However, some PVC materials may deteriorate if progressively treated with hydrocarbons and some adhesives may also dissolve. The other disadvantage of hydrocarbon is it takes longer to evaporate from bulky parts of clothing such as shoulder pads. It can leave small traces of oily residue, which can cause allergies in some people. Although the hydrocarbon solvents are classified as combustible, they do not pose a high risk of fire or explosion when stored and handled properly. However, they can contain traces of volatile organic compounds, which can form smog.
2. **Modified hydrocarbon blends (Pure dry):** These are compound prepared from hydrocarbons by modifying their properties.
3. **Glycol ethers:** Glycol ethers (dipropylene glycol tertiary-butyl ether) in several instances are more effective than perc and are eco-friendly. Various brand names for these products include Rynex, Solvair, Caled Impress and CaledGenX. One of the glycol ethers "Dipropylene glycol tertiary butyl ether (DPTB)" has a flash point well above the industrial specification. The ability of removing stains (water soluble) is equivalent or better than perc and other glycol ethers. The waste of DPTB can be easily separated by azeotropic distillation at lower boiling point.
4. **Liquid silicone or siloxane:** Liquid silicone (decamethylcyclopentasiloxane or D5) is a colorless, odorless and non-oily fluid, which can be used for dry-cleaning with more gentle action and without any color loss [43]. The popularity of siloxane is growing as it is considered as a green solvent. As siloxanes hardly react with the textiles, the textile items retain their color and

quality. The use of liquid silicone need licensing as it is in the list of the property of "Green Earth Cleaning (GEC)". Although it is eco-friendly, the cost is almost double of perc and GEC need to be paid for the annual affiliation fee. It produces waste which is nontoxic and nonhazardous. It can degrade within a few days in the environment in the presence of silica and traces of water and CO₂. The research on female rats by Dow Corning established the fact that exposure to the solvent can increase the incidence of tumors. However, male rats were not affected by the exposure. Further research conducted on humans' established that the threats observed in rats are not relevant to humans in this case due to the differences in the biological pathways.

5. **Liquid CO₂:** the use of liquid CO₂ is found to be superior to the commercial methods of dry-cleaning using perc [44]. However, the cleaning efficiency of liquid CO₂ is fairly low compared to perc. The equipment used for liquid CO₂ are more expensive than perc equipment, which makes it difficult for small or medium business to afford. The environmental impact of CO₂ use is very low as the clothing does not emit volatile compound. In addition, CO₂ cleaning can also be used for fire- and water- damage restoration as it is effective in the removal of toxic residues, soot and associated odors of fire. CO₂ is nontoxic, it does not persist in clothing and its greenhouse gas impact is lower than that of majority of organic solvents. Some commercial dry-cleaners use enzymes, which are equivalent to liquid CO₂ and more environmentally sustainable.
6. **Brominated solvents:** These are n-Propyl Bromide based solvents with higher KB Value than perc (*Kauri-butanol* or *KB value* is an international terminology used to measure the solvency power of a solvent based on hydrocarbon, which is specified in the ASTM standard: *ASTM D1133*). The higher KB value helps in the faster cleaning than perc. However, improper use can damage the buttons, sequins and beads. It is available in trade names such as Fabrisolv and DrySolv. In dry-cleaning, exposure to the solvent does not pose any health risk. Therefore, it is being approved by the EPA as a significant new alternative solvent compared to traditional hazardous solvents. However, excessive exposure can lead to numbness of nerves. Although the solvent is expensive, the cost is counterbalanced by its faster cleaning action, lower temperature and quick dry times. The overall dry-cleaning cost per garment is found to be the same or lower compared to perc.

IV. CONCLUSIONS

Protective clothing is designed to preserve protection as the primary function for wearer's safety. These garments need to be cleaned and maintained after use without impairing their performance and comfort properties. Generally, the cleaning process used for these garments include dry-cleaning (using solvents) or wet cleaning (using water). These cleaning processes can alter the fabric surface properties, dimensions,

physical and mechanical properties. Furthermore, the cleaning methods adapted can change the comfort features of the clothing, which may become uncomfortable to wear for extended periods.

New developments in fiber technology (such as microfibers, nanofibers and specialty fibers) and finishes extend the analytical aspect of garment manufacture. Similar developments in other areas (such as laundering chemicals and techniques) are necessary to cope with these advanced materials. Products with advanced fibers and finishes will also require the development of new care instructions; hence, the existing care instruction process should be updated accordingly.

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