DOI: 10.7251/QOL1701056R UDC: 746.1:684.75

Overview paper

Applying of Different Fabrics For Design of the Protective Military Clothes

Sanja Risteski, Vineta Srebrenkoska, Silvana Zhezhova
Faculty of Technology, University Goce Delchev – Shtip, R. Macedonia, Shtip,
sanja.spasova@ugd.edu.mk, silvana.zhezhova@ugd.edu.mk, vineta.srebrenkoska@ugd.edu.mk

Abstract: The process of designing protective military clothes is a long process based on the application of new generation of materials and searching for new trends in the field of protective clothing. The first step in the process of designing protective clothes includes the entire design activity for new products development with special emphasis on the applying of the types of new high-performance fibers for protection of the soldiers. The right selection of materials means better protection and higher satisfaction of both, the wearer and the technologist.

In this paper the main characteristics of the fabric materials used in protective clothes design are presented and the selection of the best materials for the required level of protection is made. The selected materials for design of protective clothes are analyzed and their main characteristics are presented. It is also clear that the armour should be as comfortable as possible and appropriately light.

Key words: fabric, design, protective clothes, materials.

Introduction

The history of the development of armour and arms begins with that of the human race. Humans throughout recorded history have used various types of materials to protect themselves from injury in combat and other dangerous situations. At first, protective military clothing and shields were made from animal skins, and people used the “mimicry” by which they achieved the blurred silhouette that would be less visible for enemy forces. As civilizations became more advanced, wooden and metal shields came into use (Global Security, 2011; Badea, 2011).

In medieval period armour was considered as the most reliable protection. Later, with the discovery of firearms, the traditional protection did not give the necessary results. One of the oldest records of soft protection was in medieval Japan, where people used silk fabric to protect their body from injuring which gave good results only for low speed bullets. During World War I most of the participating countries developed various forms of protective devices for the torso and the extremities, but the excessive weight or lack of adequate protection restricted their general use in combat. Studies of casualties of British forces through 1916 indicated that more than three-quarters of the wounded men could have been saved if some form of armor had been worn. Studies of French casualties showed that 60 to 80% of all wounds were caused by missiles of low to medium velocity. In addition, the British engineers studied a 6-pound body shield that was approximately 1 inch thick and was made of many layers of linen, cotton, and silk hardened by a resinous material (Gambetta, 2001; Alil, Badea and Ilie, 2014).

The next generation of ballistic clothes was introduced during World War II. The US military started researching and issuing what became known as “flak jackets” during this period. The flak jackets also included steel plates sown into cloth. They hung over the chest and stomach like a catcher’s chest protector, but they were pretty heavy. There was a helmet that completed the ensemble. The development of technology and the creation of artificial fibers create a perfect base for production of protective clothing with a higher level of protection (Beyer, Enos and Holmes, 2009; Комиссаржевский, 2005).

The appearance of synthetic fibers leads to a development of better protective systems. Although the basic idea of spreading the load over a large area is still applied, it is better to dissipate the energy of impact by deformation and breaking the protective material. The nylon, based on its high strength and module of elasticity, was thought to be ideal for ballistic protection. The next step was the use of aramid fibers due to the fact that ballistic protection process is a complex phenomenon involving the transverse velocity propagation, tensile properties and the fine structure. In the recent years, ultra-high modulus polyethylene (UHMPE) fibers, which have been produced by gel spinning, have an increased application in the ballistic protections systems, based on their properties which are better than the previous mention fibers (Turco and Glogar, 2010; Encyclopedia II, 2016). When it comes to a protective clothes design, no armour design is suitable for all the situations, and all levels of protection. For users, the comfort, degree of mobility and maximum protection against injury/trauma are very important, while for technologists, the level of required protection, time span for the required protection and energy absorption characteristics are important. For designers, it is important all these characteristics such as: comfort, lightweight, and functional model of protective clothes to be put together in advanced (Bajaj and Sriram, 1997; Abbott, 1982).

In this review, a brief account of various fibers used for protective military clothes has been given. The construction of fabrics, the research of the market needs and working performance of protective clothes design has also been discussed.

Design demands and fiber selection

Soldiers need to be protected from bullets and others projectiles like shrapnel's metal fragments and flying penetrating debris of various sizes, shapes and velocity. The bullet resistant clothing has to stop the bullet from penetrating and absorb its kinetic energy, converting it into work of deformation. The primary factors which influence the performance of bulletproof material are strength, modulus and elongation at break, deformability of the projectile and the velocity of transverse shock wave in the fiber (Roerdink and Van Dingenen, 2002)

The design of protective clothes involves selection of materials or their combination that will be resistant to impact, and determining the number of layers of material that is needed to prevent penetration of bullets and trauma effect. The final weight is a very important factor in the process of designing protective clothes. The goal is to design protective clothes that will give the required protection which is determined with the right selection of materials, and the design should ensure comfort and unrestricted movement. The weight of the clothes should be light and the clothes should be easily removable. The mobility of the hands and knees should be provided, and clothes should have adequate length that will not affect the mobility of the body. The design of the protective clothes should not contain harsh, sharp or hard surfaces, it cannot have overweight or it cannot be too tight/loose, and the material should provide resistance to air and water vapor. There are different types of materials that are used for ballistic protection, depending on the use and the level of protection. The protective function of the clothing could be achieved through standard technologies for the textile industry or application via new technologies (ISO, 2001). The process technology for given protective clothing is different and it generally includes: production or selection of material, production of fabrics or other similar products, finishing and designing clothes. The chemical structure determines the characteristics and performance of each type of fiber. The natural fibers are one of the most important classes of fibers used for protective clothing. However, the appearance of synthetic and regenerated fibers and especially high-performance fibers has become so broad that virtually any type of protective clothing could find adequate fibers (ISO, 1999; Scott, 2005). Early soft body armor was made of nylon (polyamide) and had fairly poor ballistic performance. It required many thick layers for increased effectiveness.

Comparative characteristics for the polyamide, aramide and polyethylene fibers used in ballistic protection clothes are presented in Table 1. These fibers have provided body armor with extraordinarily improved ballistic protection levels at a significantly reduced weight - a potent combination for enhancing the effectiveness and mobility of military troops. These types of fibers are used in protective wear developed for impact protection and in textile reinforcement products for different applications (Iures, 2007). For the ballistic protection, the degree and the mechanism of impact energy absorption is very important. The specific modulus and the density determine the velocity of the shock wave propagation into the fiber. Moreover, the specific modulus and the sonic velocity in fiber determine the ballistic potential of the textile complex. The capacity of impact energy absorption is determined by the tenacity and elongation of the yarn (Kumar, 1991).

Table 1. Comparative characteristics for the fibers used in ballistic protection clothes

Fiber type	Density, g/cm^3	Tenacity, N/Tex	Specific modulus, N/Tex	Elongation at break, %	Sonic velocity, m/s
Polyamide	1.14	0.80	5	20.0	2200
Aramide	1.44	2.35	52	3.6	8200
Polyethylene	0.97	3.30	101	3.7	10.000

Nowadays, on the market, for ballistic protection equipment is known these types of fibers: polyamide and aramide fibers: Kevlar® (Du Pont) Twaron® (AKZO) Technora® (Teijin) and high tenacity polyethylene fibers: Dyneema® (DSM) Spectra® (Allied Signal).

Polyamide (nylon) fibers are fibers that are mostly used for soft protection in the military protective clothes industry for the following features and characteristics:

- they are fibers with excellent el1asticity and agility in deformations,
- moderately hydrophilic absorption of moisture of 4 to 5% for normal conditions and of 9% at 100% relative humidity. They have moderate conductivity of heat and remain stable at temperatures below 150° C,
- have high electrical resistance and easily create static electricity (Kuklane and Holmer, 2000).

Ultra-high molecular weight polyethylene fibers (UHMWPE) are used in the industry for protective clothes for the following characteristics:

- they have an extremely high specific strength and modules,
- high chemical resistance and high abrasion resistance (Hearle, 2001).

Dyneema® fibers provide maximum protection and at the same time lighter, flexible solution that enhances comfort, mobility, and efficiency. It is highly resistant to corrosive chemicals except oxidizing acids, it has extremely low moisture absorption and a very low coefficient of friction, it is self-lubricating, and it is highly resistant to abrasion. Strength-to-weight ratios for Dyneema® are about 40% higher than for aramid.

Spectra® fibers are one of the strongest and lightest available fibers. The bright white polyethylene is 15 times stronger than steel, more durable than polyester and has a specific strength that is 40% greater than aramid fiber (Karacan, 2005).

Aramid fibers - used in industry of protective clothes for the following characteristics:

- high tensile strength, high modulus, low density,
- good vibration damping, high energy absorption and high impact resistance,
- good chemical resistance, low thermal expansion and conductivity,

- P-aramid fibers are used to ensure high strength whereas m-aramid fibers are used in protective clothes to ensure flame and heat resistance (Schwartz, 2011).

Kevlar® fibers can be used with, or as a great alternative to carbon fibers or fiberglass. Composites based on Kevlar® are lightweight, impact resistant, abrasion resistant, heat resistant, and have great strength properties for the most demanding applications.

Twaron® fibers are heat-resistant and strong synthetic fibers with a unique combination of mechanical properties, chemical resistance, excellent durability and thermal stability. Fabrics and laminates made of these fibers have wide variety of filament types, exceptional strength and durability and they are easy to integrate into production processes (Mallick, 2007).

Technora® fibers offer superlative product performance. It is eight times stronger than steel, and it has high modulus, as well as great heat and chemical resistance. These fibers are primarily used for industrial and reinforcement applications because of its high-performance properties. These fibers have exceptional strength and durability. They are resistant to heat and chemicals, long-term dimensional stability and they are adjustable to different applications.

Nomex® fibers can be used in numerous applications. They have good dimension stability and excellent heat resistance. They are widely used in protective manufacture clothes. The materials obtained from these fibers have low levels of flammability and they are melt resistant at high temperatures. They are highly durable in strength compared to carbon fiber, but have less strength under compression. They possess a high degree of molecular orientation resulting from dense linear molecules as well as from being inclined to form a liquid crystal solution. For these reasons, the materials obtained from these fibers are strong «candidates» in the industry for protective clothing (Hongu and Phillips, 1997; Lewin and Preston 1989).

Construction of fabrics used for ballistic protection

Two types of fabrics are used in protective clothes design: woven fabric and non-woven fabric (unidirectional) (Figure 1).

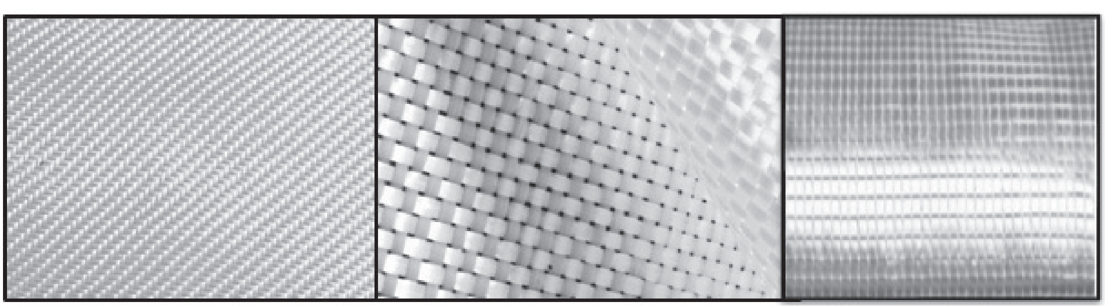

Figure 1. Examples of Woven and UD fabric Laminate Constructions

Woven textiles are the most commonly used for ballistic protection. The majority of ballistic fabrics are of plain-woven types. Continuous multifilament yarns with the minimum of twist tend to give the best results. The principal factor that dictates the design of body armors is the type(s) of threat(s) for which protection is required. Armors for protection of one threat type may not be suitable for others (Hongu and Phillips, 1997). Traditionally, soft body armors for ballistic protection were manufactured using layers of woven fabrics stitched together, but now they include laminates stacked with non-woven, unidirectional (UD) layers and combinations of woven/nonwoven laminates. The plain weave is formed by interlacing yarns of two principal families, designated “warp” and “weft,” at right angles to each other as illustrated in Figure 2.

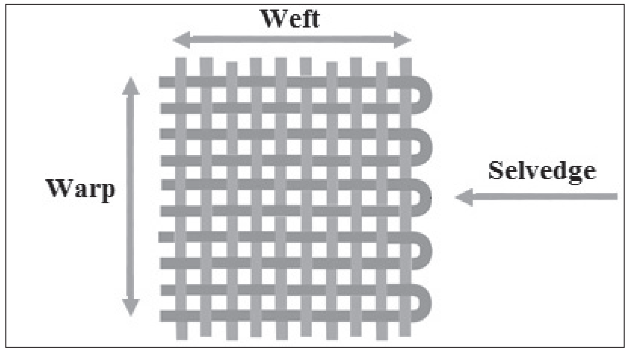

Figure 2. Warp and Weft Yarn Directions for a Plain-Woven Fabric

The UD layers are produced in very thin sheet forms and are stacked, for example, in an alternating 0°/90° cross-ply fashion. Polyethylene films are added to protect the layers and the final laminated shape is attained by applying heat and pressure. Commercial UD laminates used for ballistic protection include Honeywell's Spectra Shield (ultrahigh molecular weight polyethylene (UHMWPE) fibers) and Gold Shield (Kevlar fibers) and DSM's Dyneema (UHMWPE fibers). Today's textile-based armors, such as bullet-resistant vests and helmets, integrate many sophisticated polymer materials and textile processing technologies that are optimized across multiple dimensional scales. The architecture of the woven fabric is further described by the yarn cross-sectional dimensions, number of warp yarns per unit fabric width, number of weft yarns per unit fabric length, and cover factor-all of which affect the energy absorption levels. Additionally, the weight of the fabric is defined by its areal weight density, often expressed in grams per square meter. Several woven architectures are used in soft body armors including the plain and basket weaves shown in Figure 3.

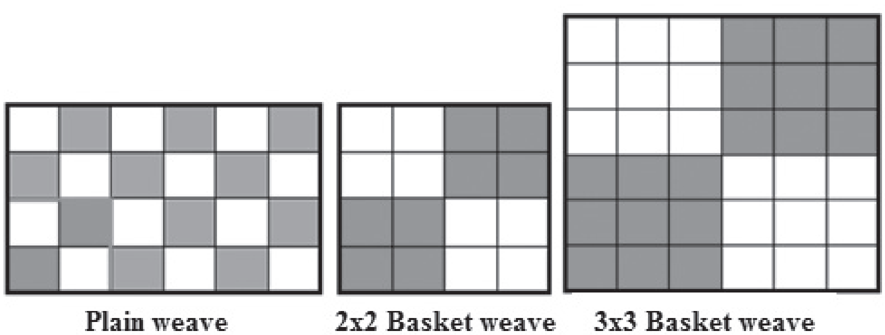

Figure 3. Plain and Basket Weave

Yarn motions, which are necessary for ballistic energy absorption, occur because of the yarn-to-yarn interactions, such as crimp interchange, shearing and friction. It is important to determine the extension and shear jamming points for ensuring proper amounts of yarn mobility that lead to optimized energy absorption levels. In general, jamming is related to the maximum number of weft yarns per unit length that can be woven into a fabric for a given warp yarn size and spacing. Friction between yarns at the crossover regions can be used to minimize yarn migrations away from the impact site and to provide a dissipative energy transfer mechanism (Cavallaro, 2011).

FUTURE DESIGN, FUNCTIONALITY AND NEW TRENDS

The protection of the used materials is a primary factor in a design of protective clothes. Factors that deserve attention are the design with low weight materials, easy adaptable to the soldier's body, comfort, permeability, maintenance, cost etc. Comfort of protective clothes becomes a bigger priority for the military. In the future, soldiers could wear customizabl1e, tailor-made body armor. That could mean more components to wear and carry, such as layers in cold weather or having special applications added to helmets that serve for a specific need, like rifle shot protection versus ballistic fragmentation protection. That means that designers and engineers have to design flexible, modifiable materials that gather or combine that requirement. The next generation "soldier protection system (SPS)," would equip troops with lighter body armor, along with upgraded equipment including health sensors and new protective eyewear. The needs of the market today are focused on finding the way to reduce weight of the body armor.

Construction form of advanced protective equipment should provide easy adaptability to the soldier's body. The materials used for protective clothes production should be easy to adapt to the shape of the soldier body. The future trends in the area of protective clothes design are focused on the construction of protective clothes with the following characteristics:

- ballistic, chemical and flame resistance,
- light wear materials used in the construction, and high protection in covering areas,
- mobile cases, pockets for plates inserts in the shoulders, side, torso, groin and back,
- modular parts,
- protection against fire and chemicals, comfort, and advanced design including (SPS) (Horrocks and Anand, 2000).

Besides the protective function, the clothes should be comfortable to conserve energy balance within the limits of tolerance for warmth or coldness of the body. When soldiers wear protective clothes and simultaneously perform hard physical labor, the body generates metabolic heat that causes thermal stress in the holder. Thermal stress or comforts have been lately issues of great interest to scientists. Thermal stress increases heart rate, body temperature, blood pressure and loss of fluids that are potentially dangerous to the health of the soldier. Advanced technologies and materials have made the production of protective clothes with high protective function and good comfort to become reality.

The use of waterproof breathable fabrics

These fabrics are used in protective military clothes because they provide protection from the loss of body heat and from weather conditions as wind, rain etc. The first material used for this purpose was leather. Nowadays, synthetic polymers such as polyvinylchloride (PVC) and polyurethane are used for this purpose. The term "breathable" implies that the fabric is actively ventilated. Breathable fabrics passively allow water vapor to diffuse through them, but still they prevent the penetration of liquid water. Production of water vapor from the skin is essential for the maintenance of body temperature. In the case of hypothermia, body loses heat more rapidly than it is able to produce it. When the physical activity stops, (if the soldier is injured), it causes decrease in body temperature. If perspiration cannot evaporate and liquid sweat is produced, the body is prevented from cooling at the same rate as heat is produced. In 1991 Lomax reported that modern breathable waterproof fabrics were claimed to be capable of transmitting more than 5000 g/m^2 day^{-1} of water vapor. By 1998 it was common to see claims of 10000 g/m^2 day^{-1}. Thus, waterproof breathable fabrics prevent the penetration of liquid water from outside to inside the clothes, but permit the penetration of water vapors from inside the clothing to the outside atmosphere. There are several methods which can be used to obtain fabrics which are both breathable and waterproof. These can be divided into three groups: densely woven fabrics, membranes and coatings.

Densely woven fabrics were developed in 1940s for military purpose and they are known as Ventile. Firstly, they were made of cotton and today they are made from synthetic microfilament yarns. Microfilaments are usually made from polyamide or polyester. The water penetration resistance of the fabric is improved by application of silicone or fluorocarbon finish. Ventile fabric has a pore size about 10 μm when it is dry and 3-4 μm when it is wet. Fabric made from microfilaments is claimed to have up to 70000 filaments per centimeter. When they are used in military, the Ventile fabric has about 6000 fibers per centimeter. Membranes are extremely thin films made from polymeric material and engineered in such way that they have a very high resistance to liquid water penetration but they allow the passage of water vapors. A typical membrane is only about 10 μm thick and it is laminated to a conventional textile fabric to prove the necessary mechanical strength, Figure 4. These fabrics, with all the advantages they have, should be incorporated in all advanced models of protective clothes (Thilagavathi, Raja and Kannaian, 2008).

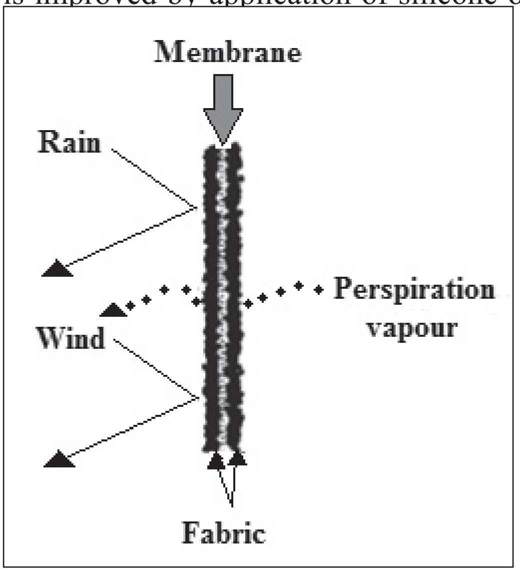

Figure 4. Typical membrane system

Conclusions

This paper presents the need of a new design concept for military protective clothes. The biggest need in the protective clothing market is to produce the right model of protective military clothes with the right use of fabrics for the required level of protection. In this paper, materials which can be used for protective clothes design and their characteristics were presented. Also, the search of the market and its needs in the field of design of protective military clothes were shown. Free movement of soldiers' body is essential and new materials should ensure comfort of the soldiers. The comfort and advanced materials and how they affect the soldiers body were also discussed. From the above it can be concluded that it is very difficult to put all these needs in the right assemble of new advanced model of protective clothes. Knowing the history of protective clothes, the new materials and trends as well as the soldier needs, the design of advanced model could fulfill all the requirements of the soldiers in 21-st century.

References

Abbott, T.A. (1982). Protective clothing. (1st ed.). Shirley Publications Manchester, UK.

Alil, I.C., Badea S. M., & Ilie, F. (2014). Considerations regarding the next generation of ballistic protective equipment such as liquid body armor. Buletin scientific, 2(38), 97-101.

Badea, S. (2011). Cercetări privind comportarea materialelor de protecţie la acţiunea undelor de şoc provocate de explozii în atmosferă. Bucharest, Military Technical Academy. (PhD Dissertation).

Bajaj, P. & Sriram. (1997). Ballistic protective clothing. Indian Journal of fibre & Textile Research, 22, 274-291.

Beyer, J., Enos, W. F. & Holmes, R. H. (2009). Personnel Protective Armor, 11, 642-687.

Cavallaro, P. V. (2011). Soft Body Armor: An Overview of Materials, Manufacturing, Testing, and Ballistic Impact Dynamics, NUWC-NPT Technical Report 12(057), 10-14.

Dammacco, G., Turco, E. & Glogar, M. I. (2010). Design of protective clothing. Faculty of Textile Technology, University of Zagreb, 1-5.

ISO 13997:1999 Protective clothing. Mechanical properties. Determination of resistance to cutting by sharp objects. Available at <http://www.iso.org/iso/home.htm> Accessed 13.11.16.

Encyclopedia II. Bulletproof vest – History. Available at <http://www.encyclopedia.com> Accessed 12.11.16

Gambetta, D. (2001). Deceptive mimicry in humans (pp. 221-241). Bodleian Library, University of Oxford.

GlobalSecurity.org. (2011). Body Armor History: Available at <http://www.globalsecurity.org/military/systems/ground/body-armor2.htm>, Accessed 28.12.16.

Hearle, J.W.S. (2001). High-Performance Fibers. CRC Press, Woodhead Publishing Ltd.

Hongu, T. & Phillips, G. O. (1997). New Fibers. (2nd ed.). Woodhead Pblishing Ltd.

Horrocks, A. R. & Anand, S. C. (2000). Handbook of Technical Textiles (pp. 282-291). Woodhead Publishing LTD and CRC press LLC.

ISO 13994:2005 Clothing for protection against liquid chemicals. Determination of the resistance of protective clothing materials to penetration by liquids under pressure. Available at <http://www.iso.org/iso/home.htm> Accessed 13.11.16.

ISO 6529:2001. Protective clothing. Protection against chemicals. Determination of resistance of protective clothing materials to permeation by liquids and gases. Available at <http://www.iso.org/iso/home.htm> Accessed 13.11.16.

Iures, L. (2007). Fibres for Building. University of Timisoara Building Faculty. Available at <http://www.library.upt.ro/pub.edocs/iures/Carte2.pdf> Accessed 23.11.16.

Karacan, I. (2005). Structure-property Relationship in High strength High modulus Polyethylene Fibers. Fibres and Textiles, 13, 15-21.

Kuklane, K & Holmer, I. (2000). Ergonomics of protective clothing, 8, 124- 130.

Kumar, S. (1991). Advances in high performance fibers. Indian Journal of Fibre & Textile research, 16, 52-64.

Lewin, M., Preston, J. (1989). Handbook of Fiber Science and Technology. High Technology Fibers Part B (pp. 22-32). Coppyright By Marcel Dekker, CRC Press.

Mallick, P.K. (2007). Fiber-Reinforced Composites: Materials, manufacturing and design. (3rd ed.). CRC Press.

Roerdink, E. & Van Dingenen, J. (2002). Past and Future of High Performance Fibers. Polymer Fibers Symposium (pp. 235-245). Heerlen.

Schwartz, M. (2011). Innovations in Materials Manufacturing, Fabrication, and Environmental Safety (pp. 467 - 470). CRC Press.

Scott, R. A. (2005). Textiles for Protection. The Textile Institute (pp. 15-17). Woodhead Publishing Limited, England.

Thilagavathi, G., Raja, A.S.M. & Kannaian, T. (2008). Nanotechnology and Protective Clothing for Defense Personnel. Defense Science Journal, 58(4), 451-459.

Комиссаржевский, Ф. (2005). История костюма, Уникальные материалы по истории костюма с древнейших времен (pp. 85-96). АСТ, Астрель, Люкс.

Recived: 17.1.2017.

Accepted: 10.6.2017.