Overview of protective clothing

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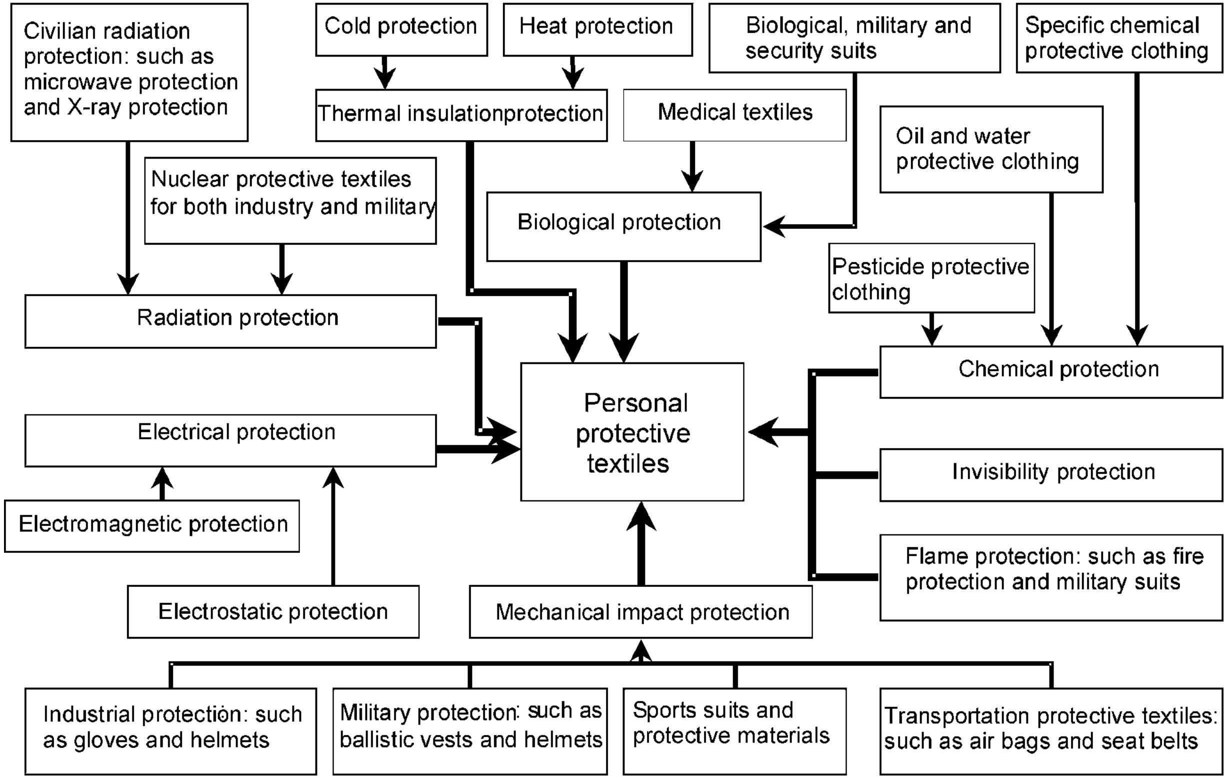
1.1 Introduction

Scientific advancements made in various fields have undoubtedly increased the quality and value of human life. It should however be recognized that the technological developments have also exposed us to greater risks and danger of being affected by unknown physical, chemical and biological attacks. One such currently relevant danger is from bioterrorism and weapons of mass destruction. In addition, we continue to be exposed to hazards from fire, chemicals, radiation and biological organisms such as bacteria and viruses. Fortunately, simple and effective means of protection from most of these hazards are available. Textiles are an integral part of most protective equipment. Protective clothing is manufactured using traditional textile manufacturing technologies such as weaving, knitting and non-wovens and also by specialized techniques such as 3D weaving and braiding using natural and man-made fibers.

Protective clothing is now a major part of textiles classified as technical or industrial textiles. Protective clothing refers to garments and other fabric-related items designed to protect the wearer from harsh environmental effects that may result in injuries or death (Adanur, 1995). Today, the hazards that we are exposed to are often so specialized that no single type of clothing will be adequate for protection. Extensive research is being done to develop protective clothing for various regular and specialized civilian and military occupations (Adanur, 1995; Bajaj *et al.*, 1992; Holmes, 2000). Providing protection for the common population has also been taken seriously considering the anticipated disaster due to terrorism or biochemical attacks (Holmes, 2000; Koscheyev and Leon, 1997).

1.2 Market prospects

Protective textiles are a part of technical textiles that are defined as comprising all those textile-based products which are used principally for their performance or functional characteristics rather than their aesthetic or decorative



1.1 Schematic classifications of protective textiles.

characteristics (Byrne, 2000). In 2000, technical textiles accounted for about 25% of all textile consumption by weight (David Rigby Associates, 2004). Protective textiles account for 1.4% of the total technical textiles with an estimated value of US$5.2 billion.

Consumption of protective clothing has increased linearly in the last ten years, and in 2010 it is expected that about 340,000 tons of protective clothing will be consumed, an increase of 85% over consumption in 1995. The Americas (mainly USA and Canada) have the highest consumption of protective clothing per annum at about 91 300 tons followed by Europe with 78,200 tons and Asia with 61,300 tons (David Rigby Associates, 2004). All other regions consume only 7,200 tons, 3.0% of total protective textile consumption.

1.3 Classification

Classifying personal protective textiles is complicated because no single classification can clearly summarize all kinds of protection. Overlap of the definitions is common since there are so many occupations and applications that even the same class of protective clothing often has different requirements in technique and protection. Depending on the end use, personal protective textiles can be classified as industrial protective textiles, agricultural protective textiles, military protective textiles, civilian protective textiles, medical protective textiles, sports protective textiles and space protective textiles.

Personal protective textiles can be further classified according to the end-use functions such as thermal (cold) protection, flame protection, chemical protection, mechanical impact protection, radiation protection, biological protection, electrical protection and wearer visibility. Their relationship is illustrated in Fig. 1.1. Unless indicated otherwise, this classification will be used in the following descriptions.

1.3.1 Fire protection

It would have been impossible for humans to survive the primitive age without the use of fire. However, fire could be dangerous. Fire disasters occur frequently resulting in non-fatal and fatal casualties. Of all the accidental fires in dwellings, occupied buildings and outdoor fires, the great majority (79% of the total in 1986) of deaths resulted from fires in dwellings although only 16% of fires happened in dwellings (Bajaj *et al.*, 1992). The most frequently ignited materials were the textiles, especially upholstery and furnishings (Bajaj *et al.*, 1992). It should, however, be noted that the main cause of death in a fire accident is not direct burning but suffocation due to the smoke and toxic gases released during burning. In the UK, 50% of fatalities in fire accidents were directly attributable to this cause (Bajaj *et al.*, 1992). Therefore, the use of non- or low-toxic burning materials is very important for fire protection.

Human tissue (skin) is very sensitive to heat. It is reported that, at 45 ºC, the sensation of pain is experienced, and at 72 ºC the skin is completely burnt (Bajaj *et al.*, 1992; Panek, 1982). The purpose of fire-protective clothing is to reduce the rate of heating of human skin in order to provide the wearer enough time to react and escape. The time that a wearer stays in flame circumstances and the amount of heat flux produced are important factors for designing the protective stratagem. Under normal conditions, only 3–10 seconds are available for a person to escape from a place of fire with a heat flux of about 130–330 kW/m^2 (Holmes, 2000). Fibers commonly used for textiles are easily burnt. Untreated cotton will either burn (flaming combustion) or smolder (smolder combustion), whenever it is in the presence of oxygen and the temperature is high enough to initiate combustion (360–420 ºC) (Wakelyn, 1997).

Protective clothing designed for flame protection must have two functions, i.e., be flame-resistant and form a heat barrier. The latter is a very important factor if the wearer needs to stay near flames for a fairly long time. In fact, the danger of burning lies with the parts of the body not covered by clothing, confirmed by statistics showing that 75% of all firefighter burn injuries in the USA are to the hands and face (Holmes, 2000). Flame-retardant clothing is generally used for occupation uniforms (Holmes, 2000).

Increasing government regulations and safety concerns necessitate that certain classes of garments and home textiles such as children's sleepwear, carpets, upholstery fabrics and bedding be made flame-retardant or resistant (Wakelyn *et al.*, 1998). Using inherently flame-retardant materials such as Kevlar and Nomex, applying a flame-retardant finish or a combination of these methods are commonly used to make clothing and textiles flame retardant.

1.3.2 Heat and cold protection

Basic metabolisms occurring inside our body generate heat that can be life saving or fatal depending on the atmosphere and circumstances that we are in. Normally, human bodies are comfortable to heat in a very narrow temperature range of 28–30 ºC (82–86 ºF) (Fourt and Hollier, 1970). In summer, we need the heat from our metabolic activity to be transferred outside as soon as possible, while in winter, especially in extremely cold conditions, we must find ways to prevent the loss of heat from our body. Heat stress, defined as the situation where the body cannot dissipate its excess heat to the environment is a serious problem especially during physical working (Bajaj *et al.*, 1992; McLellan, 1996; Muza *et al.*, 1996; Richardson and Capra, 2001; Wasterlund, 1998).

Basically, heat is transferred either as conductive, convective, radiant heat or a combination of these modes depending on the source of heat, the atmosphere the heat-absorbing material is in and the protection available against heat (Bajaj *et al.*, 1992; Fourt and Hollier, 1970). Any heat transfer will have at least one of these modes and heat protection is the method to decrease or increase the rate of heat transfer. For protection from conductive heat, fabric thickness and density are the major considerations, since air trapped between fibers has the lowest thermal conductivity of all materials (Morton and Hearle, 1997). For protection from convective heat (flame hazard in particular), the flame-retardant properties of the fabric are important. As for radiant heat protection, metalized fabrics such as aluminized fabrics are preferred, since metalized fabrics have high surface reflection and also electrical conductivity (Adanur, 1995; Bajaj *et al.*, 1992). Ideal clothing for protection from heat transfer are fabrics with thermo-regulating or temperature-adaptable properties (Bajaj *et al.*, 1992; Pause, 2003). Phase change materials (PCM) are one such example that can absorb heat and change to a high-energy phase in a hot environment, but can reverse the process to release heat in cold situations (Choi *et al.*, 2004b).

Specifically designed protective clothing is necessary to survive and operate in temperatures below −30 °C. Such low-temperature conditions are aggravated in the presence of wind, rain or snow leading to cold stress that may be fatal (Rissanen and Rintamaki, 2000). The most effective method of cold protection is to avoid or decrease conductive heat loss. Clothing designed to protect from cold is usually multi-layered, consisting of a non-absorbent inner layer, a middle insulating layer capable of trapping air but transferring moisture, and an outer layer that is impermeable to wind and water. Temperature-adaptable clothing that can protect from both heat and cold has been developed by fixing polyethylene glycol to cotton at different curing temperatures (Bajaj *et al.*, 1992).

1.3.3 Chemical protection

Fortunately, most of us are not involved in handling dangerous and toxic chemicals, since no amount of protection can provide complete isolation from the hazards of chemicals. In recent years, the chemical industry has been facing an ever-increasing degree of regulation to avoid workers being exposed to chemical hazards (Bajaj *et al.*, 1992). Chemical protective clothing (CPC) should be considered the last line of defense in any chemical-handling operation and every effort should be made to use less hazardous chemicals where possible, or to develop and implement engineering controls that minimize or eliminate human contact with chemical hazards (Carroll, 2001, Adanur, 1995).

Protective clothing cannot be made generic for all chemical applications, since chemicals vary in most cases and a particular CPC can protect only against a limited number of specific chemicals (Perepelkin, 2001). Important considerations in designing chemical protective clothing are the amount of chemical permeation, breakthrough time for penetration, liquid repellency, and physical properties of the CPC in specific chemical conditions (Carroll, 2001; Mandel *et al.*, 1996; McQueen *et al.*, 2000; Vo *et al.*, 2001; Park and Zellers, 2000; Singh and Kaur, 1997a,b). Based on the specific requirements and type of clothing, CPC is classified in different ways.

Chemical protective clothing can be categorized as encapsulating or non-encapsulating based on the style of wearing the clothing (Adanur, 1995). The encapsulating system covers the whole body and includes respiratory protection equipment and is generally used where high chemical protection is required. The non-encapsulating clothing is assembled from separate components and the respiratory system is not a part of the CPC. The Environmental Protection Agency (EPA) in the United States classifies protective clothing based on the level of protection from highest to normal protection. CPC is rated for four levels of protection, levels A, B, ºC and D from highest protection to normal protection (Adanur, 1995; Carroll, 2001). European standards for CPC are based on the 'type' of clothing based on testing of the whole garment and are classified as types 1 to 7, related to the type of exposure of the CPC such as gas-tight, spray-tight, liquid-tight, etc. (Carroll, 2001). Traditionally, used disposable clothing also offers resistance to a wide range of chemicals and some disposable clothing can be repaired using adhesive patches and reused before being disposed (Adanur, 1995; Carroll, 2001). Chemicals that are in liquid form are more often used than solid chemicals. Therefore, chemical protective clothing should be repellent or impermeable to liquids.

Developing pesticide-resistant clothing has received considerable attention from researchers since exposure of skin to pesticide is a major health hazard to farmers (Zhang and Raheel, 2003). Clothing currently used for pesticide protection does not give adequate protection, especially to the hands and thighs, even if farmers use tractor-mounted boom sprayers with a closed cabin and wear protective clothing with gloves and rubber boots (Fenske *et al.*, 2002, Elmi *et al.*, 1998).

Other important functions of chemical protective clothing are to protect from chemicals present in the air such as toxic and noxious gases or fumes from automobiles, dust and microorganisms present in the air. Safety masks containing activated carbon particles which can absorb the dust present in the atmosphere are commonly used against air pollution.

1.3.4 Mechanical impact protection

Ballistic protection

Ballistic protection is generally required for soldiers, policemen and general security personnel. Ballistic protection involves protection of body and eyes against projectiles of various shapes, sizes, and impact velocities (Adanur, 1995). Historically, ballistic protection devices were made from metals and were too heavy to wear. Textile materials provide the same level of ballistic protection as metals but have relatively low weight and are therefore comfortable to wear. Most of the casualties during military combat or during unintended explosions are from the fragments of matter caused by the explosion hitting the body (Scott, 2000). It is reported that during military combat, only 19% of casualties are caused by bullets, as high as 59% of casualties are caused by fragments, and about 22% are due to other reasons (Scott, 2000). The number of casualties due to ballistic impact can be reduced 19% by wearing helmets, 40% by wearing armor and 65% by wearing armor with helmet (Scott, 2000).

High-performance clothing designed for ballistic protection dissipates the energy of the fragment/shrapnel by stretching and breaking the yarns and transferring the energy from the impact at the crossover points of yarns (Scott, 2000). The ballistic protection of a material depends on its ability to absorb energy locally and on the efficiency and speed of transferring the absorbed energy (Jacobs and Van Dingenen, 2001). One of the earliest materials used for ballistic protection was woven silk that was later replaced by high-modulus fibers based on aliphatic nylon 6,6 having a high degree of crystallinity and low elongation. Since the 1970s, aromatic polyamide fibers, such as Kevlar® (Du Pont) and Twaron® (Enka) and ultra-high-modulus polyethylene (UHMPE) have been used for ballistic protection (Scott, 2000).

Other impact protection

According to the US Labor Department, each year, more than one million workers suffer job-related injuries and 25% of these injuries are to the hands and arms (Adanur, 1995). Gloves, helmets and chain-saw clothing are the main protective accessories used by personnel working in the chemical, construction and other industries (Adanur, 1995). Some examples of non-combat impact protection are the seat belts and air bags used in automobiles. Air bags have reduced the death rate in accidents by 28%, serious injuries by 29% and hospitalization by 24% and seat belts can reduce fatal and serious injuries by 50% (Adanur, 1995, Fung, 2000). A typical seat belt is required to restrain a passenger weighing 90 kg in collision with a fixed object at 50 km/h (about 30 mph). The tensile strength of a seat belt should be at least 30 kN/50mm (Fung, 2000).

Although sports and recreational injuries account for relatively few deaths (0–6% of deaths to those under age 20), these activities are associated with 17% of all hospitalized injuries and 19% of emergency room visits to hospitals (Mackay and Scanlon, 2001). Child and adolescent deaths due to sports and recreational injuries are a major cause of morbidity in Canada (Canadian Institute of Child Health, 1994). In 1995, Canada spent about $4.2 billion in treating unintentional injuries (Mackay and Scanlon, 2001). More than half of the total sports and recreational injuries are attributed to eight activities: ice hockey, baseball, basketball, soccer, jogging, cycling, football and volleyball. Modern sports clothing uses high-performance fabrics that are designed to operate at high speed but are still safe and comfortable to wear (O'Mahony and Braddock, 2002). The most common protective textiles used in sports are in knee braces, wrist braces, ankle braces, helmets and guards.

1.3.5 Biological protection

Most natural textile fibers such as wool, silk and cellulosics are subject to biological degradation by bacteria, dermatophytic fungi, etc. Fortunately, various chemicals and finishing techniques are available that can protect the textile and the wearer from biological attacks. Textiles designed for biological protection have two functions: first, protecting the wearer from being attacked by bacteria, yeast, dermatophytic fungi, and other related microorganisms which cause aesthetic, hygienic, or medical problems; secondly, protecting the textile itself from biodeterioration caused by mold, mildew, and rot-producing fungi and from being digested by insects and other pests (Bajaj *et al.*, 1992; Vigo, 1983).

The antimicrobial properties of silk have been used for many years in medical applications (Choi *et al.*, 2004a). Natural fibers contain lignin and other substances that have inherent antimicrobial properties. Generally, textiles made from natural fibers have better anti-microbial properties than man-made fibers due to the presence of substances such as lignin and pectin. Chemical finishing is most commonly used for imparting anti-microbial properties to natural and man-made textiles by applying functional finishes onto the surface of the fabric or by making fibers inherently resistant to microorganisms.

In high functional fibers that are inherently anti-microbial, the entire surface of the fiber is made from a bioactive material and the bioactivity remains undiminished throughout the useful life of the fiber (Bajaj *et al.*, 1992; Patel *et al.*, 1998, Rajendran and Anand, 2002). In some cases, just providing an anti-microbial finish to the fabrics may not prevent the infection. For example, fungi such as *Aspergillosis* is fatal to about 80% of bone marrow and organ transplant recipients, even with intense hospital and strong antifungal drug treatment (Curtis, 1998). To prevent such trans-infection through fabrics, combined fluid-resistant and anti-microbial finishing have been developed that can avoid fluid penetration through the fabric and decrease the trans-infection (Anonymous, 2003; Belkin, 1999; Kasturiya and Bhargave, 2003; Shekar *et al.*, 2001; Zins, 1998).

Fabrics designed for microbial protection should act as barriers to bacteria and other microorganisms that are believed to be transported from one location to another by carriers such as dust or liquids (Belkin, 1999, 2002; Leonas and Jinkins, 1997). Films generally have high barrier properties against microbes and chemicals. However, films when used with fabrics to provide antimicrobial properties make fabrics impermeable to airflow leading to heat stress and other physiological problems that may be fatal (Wilusz *et al.*, 1997). New membrane structures called 'perm-selective' or 'breathable' membranes have been developed that can prevent airflow through the fabric layer but have high water-vapor permeability. Using these membranes with fabrics provides effective protection from hazardous materials or microbes without causing heat stress (HAZMAT) (Schreuder-Gibson *et al.*, 2003).

Risks and contaminations caused by HIV and other viruses have increased the protective requirements for medical textiles (Rajendran and Anand, 2002; Patel *et al.*, 1998). It is desirable to have anti-microbial finishing even for everyday textiles such as underwear, baby suits, diapers, towels, etc.

1.3.6 Radiation protection

Nuclear radiation protection

Special clothing to prevent exposure to radiation is needed for people working in radioactive environments. Alpha-, beta- and gamma-radiation are the major modes of nuclear radiation. Irradiation injuries by alpha- and some beta-radiation can be prevented by keeping the radioactive dirt off the skin and out of the eyes, nose and mouth. Goggles, respiratory masks, gloves and lightweight protective clothing may be adequate for protection from some alpha- and beta-radiation which have weak penetration (Adanur, 1995). However, gamma- and some beta-radiation have sufficient energy to penetrate through textiles and can affect the human tissue even if the radioactive substance does not contact the human skin. Protection from transmitted radiation depends on the level of contamination control, exposure time, distance from radiation source and the type of radioactive shield available (Adanur, 1995). Shielding is done by placing a dense (heavy) radiation barrier such as lead between the radioactive dirt and the worker.

Woven cotton, polyester/cotton or nylon/polyester fabrics with a twill and sateen weave are the major types of fabric forms used for nuclear protective clothing (Adanur, 1995). Non-woven fabrics used as over- and transit garments in nuclear radiation protection act as a barrier against dangerous particles, shields the main garment against contamination and are disposable when contaminated (Bajaj *et al.*, 1992).

UV radiation protection

The wavelength of solar radiation reaching the Earth's surface spans from 280 to 3,000 nm (Reinert *et al.*, 1997). Ultraviolet (UV) light has the highest energy radiation consisting of UV-A and UV-B, whose radiation is from 320–340 nm and 280–320 nm, respectively. Excessive exposure of the skin to UV-A radiation can be carcinogenic resulting in chronic reactions and injury, accelerated ageing of the skin, promotion of photodermatosis (acne) etc. (Reinert *et al.*, 1997). An overdose of UV-B can lead to acute and chronic reactions, skin reddening (erythema) or sunburn, increasing the risk factor of persons susceptible to melanoma and skin cancer (Gies *et al.*, 1997, 1998; Reinert *et al.*, 1997; Wang *et al.*, 2001). In the last decade, attempts to reduce the incidence of skin cancer were mainly focused on decreasing solar UVR exposure (Gies *et al.*, 1997).

Table 1.1 Main factors affecting UVR protection (Adanur, 1995; Gies *et al.*, 1997, 1998; Reinert *et al.*, 1997; Xin *et al.*, 2004)

Factors	Effectiveness
1. Fiber	Cotton has high permeability to UVR, Wool has high absorption, Polyester has high absorption to UV-B, polyamides are fairly permeable to UVR.
2. Weave	Fabric construction, which determines the porosity and type of weave, is the most important factor affecting UV protection. Tighter the weave, lesser the UVR transmitted.
3. Color	Dark colors absorb UVR more strongly and therefore have high UPFs.
4. Weight	Thicker and heavier fabrics transmit less UVR.
5. Stretch	Greater the stretch, lower the UPF rating.
6. Water	Depends on the moisture absorption capabilities of the fibers/fabrics. Generally, fabrics provide less UVR protection when wet.
7. Finishing	UVR absorbing additives can be used to increase the protection of lightweight summer garments.

Although many terms such as SPF (sun protection factor), and CPF (clothing protection factor) which are generally used in the UK have been used to designate the amount of solar UVR protection of fabrics, UPF (ultraviolet protection factor) is the most commonly used index (Gies *et al.*, 1997, 1998; Hatch, 2002; Wang *et al.*, 2001; Xin *et al.*, 2004). The UPF for clothing with an excellent UV protection should be 40 to 50+ (Gies *et al.*, 1997). But from a clinical viewpoint, a UPF greater than 50 is entirely unnecessary (Gies *et al.*, 1997). Sunscreens, sunglasses, hats and clothing are the main accessories used to protect from UVR. Textiles are excellent materials for UVR protection and most UV can be blocked by common clothing (Reinert *et al.*, 1997). As shown in Table 1.1, the UVR protection of a fabric depends on fiber content, weave, fabric color, finishing processes, the presence of additives, and laundering (Gies *et al.*, 1997, 1998; Wang *et al.*, 2001; Xin *et al.*, 2004).

Electromagnetic-radiation protection

With the development of modern society, people greatly benefit from the electrical and electronic devices used during work and everyday life. However, these devices are capable of emitting radio frequencies that are potential hazards to health. Examples are cell phones with frequencies from 900 to 1,800 MHz, microwave ovens with 2,450 MHz, radar signal communication systems extending from 1 to 10,000 MHz, and so on (Cheng and Lee, 2001; Su and Chern, 2004). Many countries are legislating new regulations so that the manufacturers of electrical and electronic equipment comply with the electromagnetic (EMC) requirement standards (Cheng and Lee, 2001).

When electromagnetic waves enter an organism, they vibrate molecules producing heat that could obstruct a cell's capability for regeneration of DNA and RNA (Su and Chern, 2004). Furthermore, electromagnetic waves can cause abnormal chemical activities that produce cancer cells leading to leukemia and other types of cancer (Su and Chern, 2004).

Traditionally, sheet metals are used for shielding radio frequencies (Cheng and Lee, 2001). In recent years, conductive fabrics have been used for shielding electromagnetic and static charges in defense, the electrical and electronic industries. General textile fibers have sufficient insulating properties with resistivities of the order of $10^{15}\ \Omega/cm^2$, much higher than the desirable resistivity for electromagnetic shielding applications (Cheng and Lee, 2001). The desired resistivities for anti-electrostatic, statically dissipated and shielding materials are 10^9 to $10^{13}\ \Omega/cm^2$, 10^2 to $10^6\ \Omega/cm^2$ and lower than $10^2\ \Omega/cm^2$ respectively (Cheng and Lee, 2001). Therefore, conductive fabrics are designed according to specific requirements using various techniques such as:

1. Laminating conductive layers onto the surface of the fabric by using conductive coatings, zinc arc sprays, ionic plating, vacuum metallized sputtering, and metal foil binding (Adanur, 1995; Bajaj *et al.*, 1992; Cheng and Lee, 2001; Kirkpatrick, 1973; Last and Thouless, 1971).
2. Adding conductive fillers such as conductive carbon black, carbon fibers, metal fibers (stainless steel, aluminum, copper) or metal powders and flakes (Al, Cu, Ag, Ni) to the insulating material (Bhat *et al.*, 2004; Cheng and Lee, 2001; Miyasaka, 1986).
3. Incorporating conductive fibers and yarns into a fabric. This method provides flexibility in designing the conductive garments (Adanur, 1995; Bajaj *et al.*, 1992; Cheng and Lee, 2001, Su and Chern, 2004).

1.3.7 Electrical protection

Electromagnetic protection

Protection from electromagnetic sources is required because people who work close to power lines and electrical equipment have the possibility of being exposed to electric shocks and acute flammability hazards. Generally, rubber gloves, dielectric hard hats and boots, sleeve protectors, conductive Faraday-cage garments, rubber blankets and non-conductive sticks are used for electromagnetic protection (Adanur, 1995). Conductive protective clothing with flame resistance, known as 'Live line' garments, is necessary for people who work in the vicinity of very high-voltage electrical equipment. A live-line garment which was introduced in the early 1970s is still in use (Adanur, 1995).

Radiation from electro-magnetic fields (EMF) generated by power lines is another potential risk to people working near power lines. There have been reports about the relation between exposure to electromagnetic fields and health hazards like leukemia and brain cancer (Adanur, 1995). A typical electromagnetic protective fabric is woven from conductive material such as spun yarns containing a mixture of fire-retardant textile fibers and stainless steel fibers (8–12 micron diameter). It has been shown that fabrics made of 25% stainless steel fiber/75% wool blend or 25% stainless steel fiber/75% aramid fiber blend can protect the wearer from electromagnetic fields generated by voltages of up to 400 kV (Adanur, 1995). Protection at even higher voltages can be obtained by using a combination of these fabrics in two or more layers (King, 1988).

Electrostatic protection

Electrostatic charges accumulate easily on ordinary textile materials, especially in dry conditions (Holme *et al.*, 1998; Kathirgamanathan *et al.*, 2000; Morton and Hearle, 1997). Charges once accumulated are difficult to dissipate. The dissipation of an electrostatic-charge occurs through shocks and sparks which can be hazardous in a flammable atmosphere. Therefore, the presence of a static charge in textiles can be a major hazard in explosives, paper, printing, electronics, plastics, and the photographic industry (Bajaj *et al.*, 1992). Before the advent of non-flammable anaesthetics and anti-static rubber components in operating theatre equipment there was evidence of static electrically initiated explosions in hospitals (Scott 1981). The charge present in a garment can probably be over 60 kV depending on the balance between the rate of generation and the rate of dissipation of the static charges and the body potential (Holme *et al.*, 1998).

The clinging of garments is a common problem caused due to the presence of electrostatic charges. Electrostatic attraction may impede the opening of parachutes and even lead to catastrophic failure under certain circumstances (Holme *et al.*, 1998). Anti-electrostatic finishes are used for textiles both in civilian and non-civilian applications. The basic principle of making an antistatic garment is to decrease the electrical resistivity or the chance of electrostatic accumulation in a fabric. Examples of the former are spinning yarns containing conductive materials, producing a composite fiber in which at least one element is a conductive material or a fiber containing a conductive material such as metallic or carbon coatings (Holme *et al.*, 1998). Examples of the latter are the addition of a mixture of lubricants and surfactants to the textiles, or anti-static finishing (Holme *et al.*, 1998). It should, however, be noted that electrostatics can be very useful for practical industrial applications. In the textile industry, electrostatics are used as a means of spinning fibers and yarns (Holme *et al.*, 1998; Morton and Hearle, 1997).

1.3.8 Reduced visibility protection

Reduced visibility contributes to fatal pedestrian accidents. It is reported that night-time vehicles hit and kill more than 4000 pedestrians and injure more than 30,000 pedestrians annually in the United States (Adanur, 1995). High-visibility materials (HVM) are believed to be capable of assisting in avoiding worker and pedestrian deaths or serious injuries. HVMs are used by pedestrians, highway workers, cyclists, joggers, hikers, policemen, firemen and other professionals.

Clothing is made highly visible by sewing high-visibility materials or by chemical finishing. There are three major types of high-visibility products:

1. Reflective materials which shine when struck by light; e.g., reflective microprism
2. Photoluminescent materials that can absorb daylight or artifical light, store the energy and emit a green yellow glow in darkness
3. Fluorescent materials (Adanur, 1995).

In some cases, combinations of these methods are used to provide optimum visibility during the night.

1.4 Materials and technologies

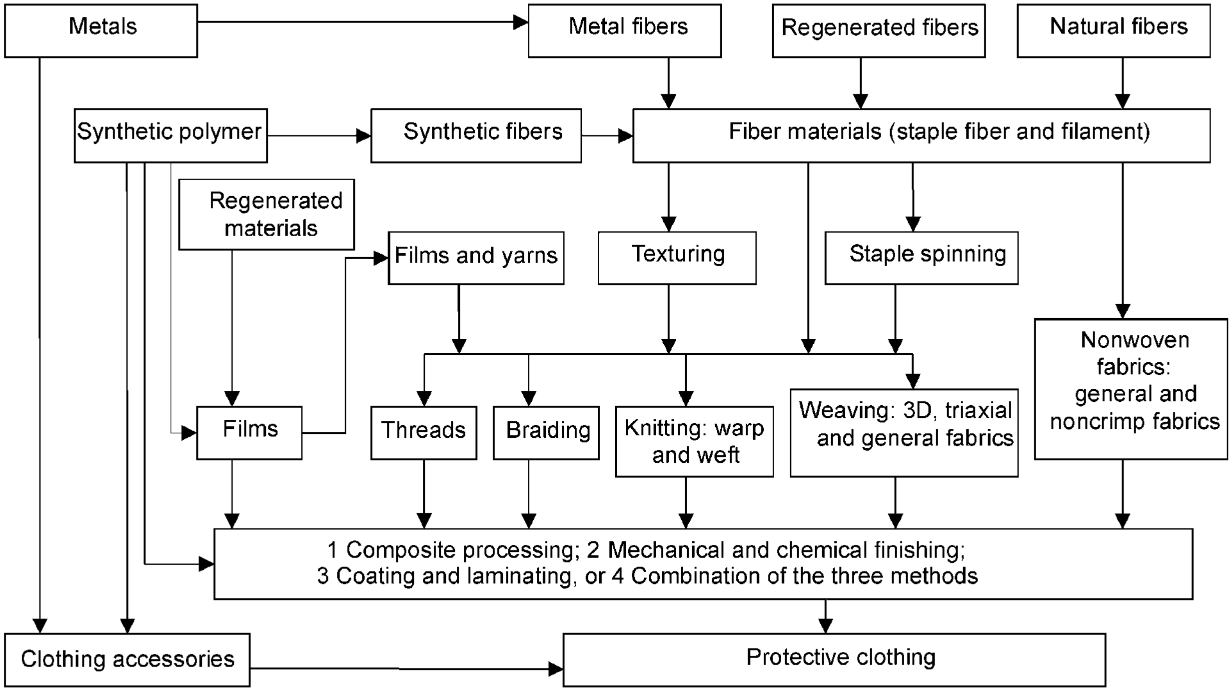
As discussed above, there exists a wide variety of personal protective clothing manufactured to suit a particular end use requirement. Protectivity can be imparted to clothing using standard textile manufacturing technologies or by any applicable new technologies. Except for a few items such as safety belts, air bags, safety ropes and parachutes, most personal protective material will be made into apparel. Although the processing technologies for specific protective clothing are different, the main processes as shown in Fig. 1.2 generally include (i) material manufacturing or selection; (ii) producing fabrics and other related items; (iii) finishing, and (iv) clothing engineering.

1.4.1 Fibers/yarn

Chemical structure

Generally, chemical structure determines the properties and performance of any fiber. Natural fibers are one of the main fiber classes used for protective clothing (Adanur, 1995; Bajaj *et al.*, 1992). However, with the emergence of man-made fibers (regenerated and synthetic fibers, especially high-performance fibers), the fiber family has become so wide and resourceful that fibers are available to meet virtually any requirement for protective clothing.

The most important man-made fibers used in personal protective clothing are:



1.2 Schematic of materials and technologies for manufacturing protective textiles.

1. *Synthetic fibers with high mechanical performance*. Fibers in this category have superior strength and high modulus that make protective clothing capable of sustaining high-velocity impacts and retaining their shape during and after impact. High performance polyimide fibers with common commercial names such as Kevlar® (Dupont) and Twaron® (Akzo, now Acordis) are polymerized from a monomer of *para*-aramids using liquid crystalline spinning (Miraftab, 2000; Weinrotter and Seidl, 1993; Doyle 2000). Polyimide fibers have excellent thermal resistance with a high glass transition temperature of about 370 ºC and do not melt and burn easily but are prone to photo-degradation (Miraftab, 2000). Another important high mechanical performance fiber is ultra-high molecular weight polyethylene (UHMWPE) fiber that has a modulus in excess of 70 GNm^{-2} and strength per specific weight is claimed to be 15 times stronger than steel and twice as strong as aromatic polyamides. But, UHMWPE melts at around 150 ºC. These fibers are now widely used in strengthening composite materials for mechanical impact protection. PBO (poly-paraphenylene benzobisoxazole) with the trade name Zylon® is another important fiber that possesses superior heat resistance and mechanical properties (Doyle, 2000; Khakhar, 1998).
2. *Combustion-resistant organic fibers*. The limited oxygen index (LOI) is a measure of the resistance of a fiber to combustion. Nomex and Conex, which were produced from *meta*-aramids by Dupont in 1962 and Teijin in 1972 respectively have a LOI of 29. Polybenzimidazole (PBI) produced by Hoechst-Celanese has a LOI of 42. The highest LOI of a fiber realized till now is the PAN-OX, made by RK Textiles, with a LOI of 55. These fibers can be used in flame- and thermal-resistant protective clothing without any chemical finishing (Miraftab, 2000).
3. *High-performance inorganic fibers such as carbon fiber, glass fiber and asbestos*. Carbon fiber has high mechanical properties, is electrically conductive and has high thermal resistance. Carbon fibers can be used as reinforcing fibers in composites and also for electromagnetic and electrostatic protection (Adanur, 1995; Bajaj *et al.*, 1992; Doyle, 2000). Fibers made from aluminosilicate compound mixtures of aluminum oxide (Al_2O) and silicon oxide (SiO_2) can tolerate temperatures from 1,250 to 1,400 ºC depending on their composition ratio (Miraftab, 2000). Silicon carbide (SiC) fibers have an outstanding ability to function in an oxidizing condition of up to 1,800 ºC (Miraftab, 2000).
4. *Novel fibers*. These fibers were first introduced by Japan in an attempt to reproduce silk-like properties with additional enhanced durability (Miraftab, 2000). The first generation novel fibers were microfibers, fibers with a denier similar to the silk filament. Currently, much thinner fibers have been successfully made and by using these fibers, tight weave fabrics with a density of 30,000 filaments/cm^2 can be produced (Miraftab, 2000). The

tight weaves make these fabrics impermeable to water droplets, but allow air and moisture vapor circulation. Tightly woven microdenier fabrics are an ideal material for waterproof fabrics and outdoor protective clothing. In addition to microdenier fibers, many functional fibers with superior performance properties can be produced by using multi-component polymer spinning.

Physical structure

Based on their length, fibers can be divided into filaments or staples. Natural fibers generally have an uneven physical structure both in staple and filament (silk) form. The fineness, cross-sectional shape, mechanical properties and even the color are different and vary from fiber to fiber (Morton and Hearle, 1997). The variability among fibers and their non-homogeneity are distinguishing features that provide unique properties to natural fibers. Even man-made fibers are now being produced with properties similar to natural fibers by using techniques such as texturization.

Filament fibers can be directly used for fabric manufacturing, or can be textured prior to being used for weaving. Texturing produces the so-called 'bulked yarns', 'stretch yarns' and 'crimped yarns' that impart synthetic fibers with physical properties similar to those of natural fibers (Hearle *et al.*, 2001). By blending different fibers, yarns can be made to have specific and unique functional properties. For example, blending stainless steel fibers with other fibers produces conductive yarns. Yarns can also be produced from film by first splitting the film and then twisting it into yarns (Tortora, 1978). Twisting can also combine the different yarns to produce novel yarns. Producing bi-component yarns by twisting core yarns with an elastic fiber such as lycra has become one of the main methods to produce elastic yarns and fabrics.

1.4.2 Fabric

Woven and knitted fabrics

Traditional woven fabrics are produced through interlacing of two systems of yarns (warp and weft) at right-angles. A wide variety of different fabric constructions can be made by varying the weave type, density of the yarns and the type of yarns themselves. In knitting, a single yarn or a set of yarns moving in one direction are used instead of two sets of yarns as in weaving (Tortora, 1978). Knitted fabrics are of two types, warp knit and weft knit. Knitted fabrics generally have a soft hand and higher heat-retaining properties compared with that of woven fabrics of a specific thickness or weight. Knitted structures generally have more porosity that can retain more air and therefore provide more warmth. Traditional knits have poor shape retention and are anisotropic in physical performance when compared to woven fabrics. The properties of both woven and knitted fabrics vary in the warp (wale), weft (course) and diagonal directions respectively.

The anisotropic properties of traditional woven and knitted fabrics limit their use in applications where isotropic properties are required. Tri-axial and tetra-axial fabrics have been developed to obtain isotropic properties. Tri-axial fabrics were first developed using a tri-axial weaving machine by Barber Colman Co. under license from Dow Weave and have been further developed by Howa Machinery Ltd., Japan (Road, 2001). Isotropic fabrics have higher tear and burst resistance than traditional woven fabrics because strain is always taken in two directions (Road, 2001).

Non-crimp fabrics

In both woven and knitted fabrics, yarns are crimped due to their interlacing and inter-looping. The crimped structure of yarns makes fabrics change shape relatively easily when external forces are applied to them. To avoid this, non-crimp fabrics have been developed in the last decade using a LIBA system, a modification to multi-axial warp knitting (Adanur, 1995). In the LIBA system, several layers of uncrimped yarns are stacked and stitched together along several axes by knitting needles piercing through the yarn layers (Adanur, 1995). Non-crimp fabrics are a relatively new class of textiles. These fabrics are a form of reinforcement that have the potential to overcome anisotropic deficiencies without affecting other properties (Adanur, 1995).

Braided fabrics

A braid structure is formed by the diagonal intersection of yarns without a definite warp and filling as in woven fabrics (Adanur, 1995). Braiding is one of the major fabrication methods for composite reinforcement structures. Traditional examples of braided structures for industrial applications are electrical wires and cables, hoses, drive belts, etc. (Adanur, 1995). Braiding is also commonly used in manufacturing the accessories used with normal clothing.

Non-woven fabrics

Non-wovens are textile structures produced by bonding and/or interlocking of fibers and other polymeric materials such as films using mechanical, chemical, thermal adhesion or solvents or a combination of these methods (Adanur, 1995; Smith, 2000). For some special applications, fabrics and yarns are also used as parts of a non-woven material. Although there are some exceptions, non-wovens are generally produced in one continuous process directly from the raw material to the finished fabric. This means less material handling than in a traditional textile process and therefore non-wovens are generally cheaper than woven and knitted structures (Smith, 2000). The quality of fibers required for non-wovens is generally not as high as that required for traditional fabrics. Cost advantages have been one of the major reasons for the rapid development of non-wovens in the past few decades (Adanur, 1995).

The use of non-wovens is increasing at a rate of about 11% per annum. Although non-wovens were expected to partially replace woven fabrics in both civilian and non-civilian applications, the poor durability of non-wovens, especially when washed has limited its use for specific applications (Adanur, 1995). However, non-wovens are now widely used in industrial applications such as filtration, geotextiles and medical textiles (Adanur, 1995; Bajaj *et al.*, 1992).

Composite textile materials

Composites can be defined as a combination of dissimilar materials designed to perform a task that neither of the constituent materials can perform individually (Adanur, 1995). In the last few decades, textile composites have made great progress, by imparting novel functions to fabrics or by expanding the scope of textiles, especially in high-tech applications. Textile composites are broadly classified as flexible and rigid materials. Examples of flexible textile composites are coated fabrics, automobile tires and conveyor belts (Adanur, 1995). More often, textile reinforced composites are used as rigid textile materials.

Laminated and coated fabrics

Laminated fabrics can be made by fabric to fabric, fabric to foam, fabric to polymer and fabric to film bonding. Laminating film-like materials to textiles has developed quickly in recent years. Recently, membranes with micropores that are permeable to water-vapor molecules but impermeable to liquids and other organic molecules have been developed. These membranes are called 'perm-selective' membranes, due to the selectivity they exhibit with respect to molecular solubility and diffusion through the polymer structure (Schreuder-Gibson *et al.*, 2003; Wilusz *et al.*, 1997). When used in clothing, membranes are used between the shell fabric and liner fabric providing the clothing with water-vapor permeability but resisting the permeation of organic molecules. Clothing developed using membranes provides protection from hazardous organic chemicals without affecting the comfort properties. Instead of using a membrane, foams are used to make clothing with high warmth retaining properties and also having high vapor and air permeability (Holmes, 2000).

A coated fabric is a composite textile material in which the strength and other properties are improved by applying a suitably formulated polymer composition (Abbott 2001; Adanur, 1995). Coatings used for textiles are largely limited to viscous liquids that can be spread onto the surface of the substrate. The spreading process is followed by a drying or curing process which hardens the coating so that a non-blocking product is produced (Hall, 2000b). Coated fabrics are widely used in chemical or liquid protective clothing, and also in bio-protective clothing (Adanur, 1995, Voronkov *et al.*, 1999).

Textile-reinforced composite materials

Textile-reinforced composite materials are one of the general class of engineering materials called composites (Ogin, 2000). A textile reinforced composite is made from a textile reinforcement structure and a matrix material. Textile reinforcing structures can be made of fiber, yarns and fabrics (which include woven, braided, knitted, non-woven, non-crimp) that can be preformed into various shapes and forms either as molded materials or 3D textiles (Khokar, 2001). Matrix materials can be thermoplastic or thermoset polymers, ceramics or metals.

Textile reinforced composites are most commonly used as technical materials. Main characteristics of a rigid textile composite are high stiffness, high strength and low density. Therefore, textile structural composites have a higher strength-to-weight ratio than metal composites. Another advantage of textile composites is that they can be made anisotropic (Adanur, 1995). With the use of oriented fibers or yarns in bundles or layers, textile composites can be made anisotropic so that they exhibit different properties along different axes.

Textile composites have successfully replaced metals and metal alloys in many applications such as automotives, aerospace, electronics, military and recreation (Adanur, 1995; Ogin, 2000). Whatever these materials are used for, most of them are designed to protect people from being injured against mechanical impact. The most typical textile composites used for protection are made from high-strength and high-modulus fibers for applications such as lightweight armor, ballistic helmets and vests, and add-on car armor (Jacobs and Van Dingenen, 2001). Low-density, high-strength and high-energy absorption capability are the notable characteristics of these products (Jacobs and Van Dingenen, 2001). The US army uses helmets reinforced with Kevlar that are about 15% lighter by weight and have substantially increased protection (ballistic limit (V_{50}) more than 2000 ft/sec) when compared to conventional helmets (Adanur, 1995). Laminating and molding are commonly used techniques to manufacture protective composites, but 3D textiles which are produced via 3D weaving are gaining more importance in reinforcing textile structural materials with improved properties (Khokar, 2001).

1.4.3 Finishing

Textile finishing can be roughly divided into mechanical and chemical finishing. Examples of mechanical finishing are calendering, raising, cropping, compressive shrinkage and heat setting. Chemical processes are those that involve the application of chemicals to the fabrics (Hall, 2000a). Although fibers having inherent functional properties are being commercialized, chemical finishing is still a major technology used for protective clothing due to its cost effectiveness and technological versatility. Chemical finishing can be used to impart fabrics with flame-resistant, liquid-proof, anti-electrostatic, high-visibility, anti-microbial and chemical-protective functions (Adanur, 1995; Bajaj *et al.*, 1992).

1.4.4 Sewing or assembling

Sewing or assembling protective material parts onto clothing is usually the last but a very important process for protective clothing. Most of the protective clothing has specific functions and the requirements for protective clothing may be different even with the same kind of functional protection. Designing protective clothing is a professional job that could determine the level of protection. The most advanced design of protective clothing is probably space suits, which are high-tech integrated systems assembled with many functional parts. The design of a space suit is so perfect that no problems have been related to space suits so far. Protective function, comfort and cost effectiveness are the main criteria in designing a protective clothing system.

In any protective clothing, all accessories used to make the garment should match the protective requirements. For example, in flame-protective clothing, all the accessories such as buttons and threads need flame- or thermal-resistance (Bajaj *et al.*, 1992). Professional designers and equipment are needed to manufacture protective clothing suited for a particular application. For example, in sewing, serged seam is the normal seam for exposure to non-hazardous conditions and bound seam is used as reinforcement with the binding providing strength and tear resistance, and taped seams are reinforced with an adhesive film tape which is capable of resisting water and liquid chemicals. Sealed sleeves and collars are designed to give more protection for operatives during pesticide application (Fenske *et al.*, 2002).

1.5 Future of personal protection

1.5.1 Highly functional clothing with physiological comfort

Protective clothing guards the wearer against the vagaries of nature and against abnormal environments (Fourt and Hollier, 1970). In addition to protection, clothing must also be comfortable so that an energy balance can be maintained within the limits of tolerance for heating or cooling the body (Fourt and Hollier, 1970). When wearing protective clothing while doing hard physical work, metabolic heat is generated by the body that develops heat-stress in the wearer.

Heat-stress or comfort problems have been of great interest to scientists in recent years (Cho *et al.*, 1997; Gibson *et al.*, 2001; McLellan, 1996; Richardson and Capra, 2001; Wasterlund, 1998). Heat-stress increases the rate of heartbeat, body (aural) temperature, blood pressure and fluid loss, that are potential hazards for a wearer's health (McLellan, 1996; Richardson and Capra, 2001).

Newer technologies and materials have made the production of protective clothing with high protective functions and good comfort a reality. The most typical example is the application of breathable membranes in protective clothing (Holmes, 2000; Schreuder-Gibson *et al.*, 2003). Nanotechnology, biotechnology and electronic technology have contributed to developing protective clothing that is more comfortable to wear.

1.5.2 Nanotechnology

Nanotechnology allows inexpensive control of the structure of matter by working with atoms (Wilson *et al.*, 2002). Nanomaterials, sometimes called nanopowders, when not compressed have grain sizes in the order of 1–100 nm in at least one coordinate and normally in three (Wilson *et al.*, 2002). Nanomaterials include nanopowder, nanofiber, nanotube and nanofilms. Nanomaterials are not new. Carbon black is a natural nanomaterial that is used in car tires to increase the life of the tire and provides the black color. Fumed silica, a component of silicon rubber, coatings, sealants and adhesives are also nanomaterials, commercially available since the 1940s (Wilson *et al.*, 2002). However, it was only in the last decade that people began to better understand the basic science of nanotechnology and tried to apply them in engineering (Wilson *et al.*, 2002). Nanomaterials can be made by plasma arcing, chemical vapor deposition, sol-gels, electrodeposition and ball milling (Fan *et al.*, 2003; Wilson *et al.*, 2002).

Nanomaterials are so small in size that most atoms are at the surface. Such structures will exhibit completely different properties from the normal materials in which the atoms are buried in the bulk of the substance (Wilson *et al.*, 2002). Properties of materials change dramatically when made into nanosize. Silicon made into nanotubes will have conductivity similar to metals (Bai *et al.*, 2004). A nanotube fibre made from carbon is tougher than any natural or synthetic organic fiber described so far (Dalton *et al.*, 2003). Nanomaterials such as nanotubes developed either from silicon or carbon would be very useful for producing highly functional protective clothing.

Initial research has proved that nanotechnology will be beneficial to textiles and has tremendous prospects. Nanomaterials can be added to polymers to produce nano-modified polymer fiber or applied during finishing to make nano-finished textiles (Qian, 2004). Polymer-clay nanocomposites have emerged as a new class of materials that have superior properties such as higher tensile strength, heat resistance, and less permeability to gas compared with traditional composites (Krishnamoorti *et al.*, 1996; Tanaka and Goettler, 2002). Polypropylene (PP) fiber is one of the main fibers used for textiles but PP is highly hydrophobic and is inherently undyeable. Fan *et al.* (2003) added nanoclay (montmorillononite, $(OH)_4Si_8Al_4O_{20}$ nH_2O) into polypropylene and succeeded in producing a modified nanoPP which could be dyed with acid and disperse dyes. Nanostructural materials such as nanofiber and films show great prospects for use in textiles (Qian, 2004). A lightweight multifunctional membrane made from electrospun nanofiber exhibits high breathability, elasticity and filtration efficiency (Gibson *et al.*, 2001). Using sol-gel, one of the common methods for manufacturing nanomaterials, a nanolayer of titanium was deposited onto the surface of cotton fibers that gave excellent UV protection. Nanoparticle coatings are also very useful to produce textiles fabrics with special surface effects (Wilson *et al.*, 2002).

Although nanotechnology has provided novel properties to polymers, practical applications in textiles are not yet well established. Nanomaterials have far higher surface-to-bulk ratio than normal materials (Wilson *et al.*, 2002). The high surface energy makes nanomaterials agglomerate, which could greatly reduce the strength of composites. Also, the agglomeration decreases the surface-to-bulk ratio and nanomaterials will have reduced properties.

1.5.3 Biotechnology

Animals have their own effective way of protecting themselves from predators and abnormal climatic conditions. An intriguing example of protection adopted by animals is the changing of color by chameleons to match the color of their surrounding environment. A chameleon has several layers of cells beneath its transparent skin, of which some layers contain pigments while others just reflect light to create new colors (Rohrlich and Rubin, 1975). The most often changed colors of chameleons are between green, brown and gray, which coincidently, often match the background colors of their habitat. Although we are yet to produce a fabric that can change its color with the changing background, camouflage-patterned clothing is an effective way to conceal soldiers in their surrounding environments (Scott, 2000).

Another interesting aspect of color in nature is the vivid and extraordinary fastness of color in the feathers of peacocks. Color production in nature is either due to structural coloration or pigmentation (Zi *et al.*, 2003). The color of peacock feathers is due to the 2D photonic-crystal structure that has the same size as the wavelength of light. This crystal is arranged in lattices in a number of layers called periods that can reflect light to produce colors. The variations in the lattice constants or the number of periods produce the diversified colors (Zi *et al.*, 2003). We are still unable to simulate either the chameleon or peacock color to perfection. Studies on dyes that can change color with changing conditions such as temperature and light have partially succeeded, but the change in the magnitude of color is very narrow.

Natural materials are renowned for their relatively higher strength and toughness. Spider dragline silk has a breaking energy per unit weight two orders of magnitude greater than that of high-tensile steel (Dalton *et al.*, 2003; Smith *et al.*, 1997). Spider silk is stronger than Kevlar and stretches better than nylon, a combination of properties seen in no other fiber (Service, 2002). Spider silk is considered an ideal material for protective ballistic materials (Dalton *et al.*, 2003, Osaki, 1996). Spider silk has been artificially produced by using liquid crystalline spinning (Vollrath and Knight, 2001). By successfully copying the spider's internal processing mechanisms and with precise control over protein folding combined with knowledge of the gene sequences of its spinning dopes, industrial production of silk-based fibers with unique properties can be commercialized (Vollrath and Knight, 2001).

1.5.4 Electronic technology

Wearable electronic systems are a promising area for textiles (Adanur 1995; Barry *et al.*, 2003; Park and Jayaraman, 2003). Wearable electronics are part of the so called 'smart textiles' or 'smart clothing'. A smart material is that which will change its characteristics according to outside conditions or according to a predefined stimulus (Adanur, 1995). Wearable electronics have been successfully used in some areas such as space suits and in military suits equipped with a GPS (global positioning system) (Adanur, 1995; Barry *et al.*, 2003; Park and Jayaraman, 2003).

Wearable electronic systems are being designed to meet new and innovative applications in military, public safety, healthcare, space exploration, sports and in fitness fields (Park and Jayaraman, 2003). Developments in electronic technology have made it possible to integrate innovation, intelligence and information into a wearable and comfortable infrastructure in a new generation of interactive textiles (Park and Jayaraman, 2003; Barry *et al.*, 2003). An interactive garment called the wearable mother board, or smart shirt has been developed at Georgia Institute of Technology, Georgia, USA. The smart shirt provides an extremely versatile framework for incorporation of sensing, monitoring and information-processing devices (Park and Jayaraman, 2003). Application of electronic technology will surely make protective clothing more reliable, safe and comfortable in future.

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