K.S. RANGASAMY COLLEGE OF TECHNOLOGY

(Autonomous)

TIRUCHENGODE – 637 215

COURSE MODULE

PROTECTIVE TEXTILE

Prepared by

Dr. K. SARAVANAN

Department of Textile Technology

K.S. Rangasamy College of Technology

Tiruchengode – 637 215

Overview of protective clothing

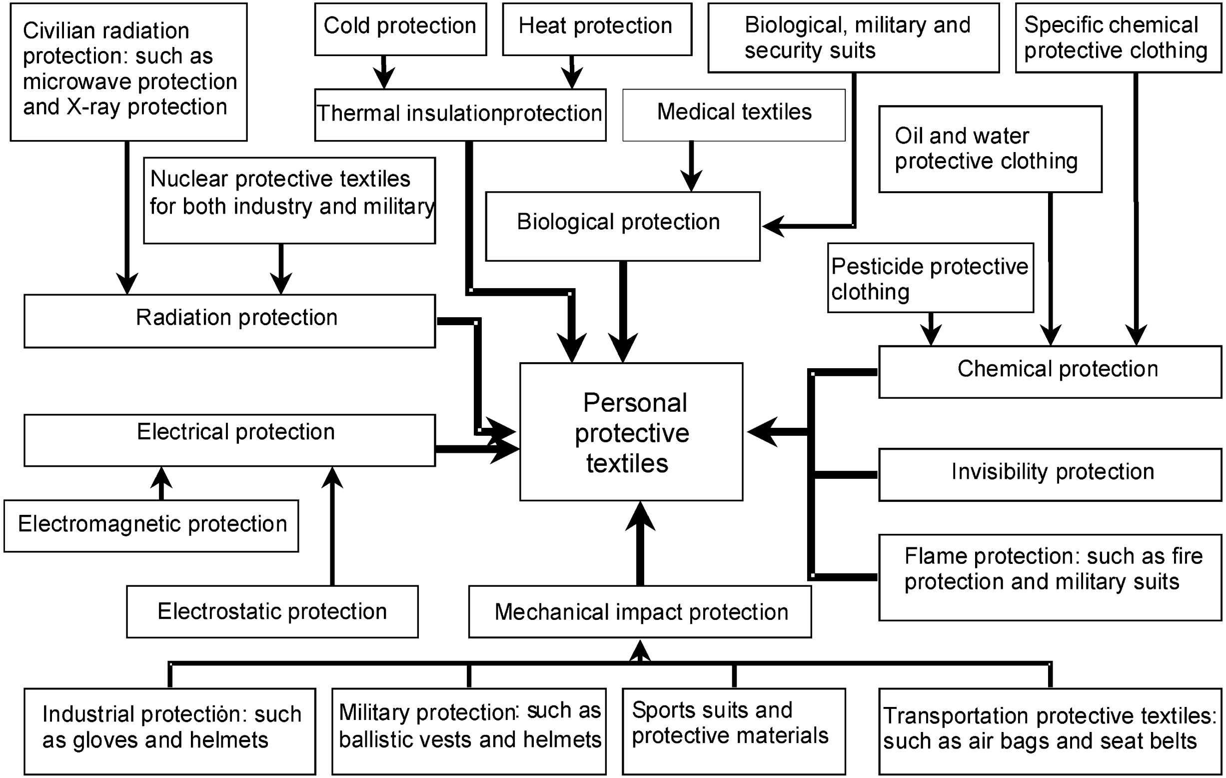
1.1 Introduction

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 thermoregulating 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, °C 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 $10^{15}\ \Omega/\text{cm}^2$, 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 $10^{13}\ \Omega/\text{cm}^2$, 10^2 to $10^6\ \Omega/\text{cm}^2$ and lower than $10^2\ \Omega/\text{cm}^2$ 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

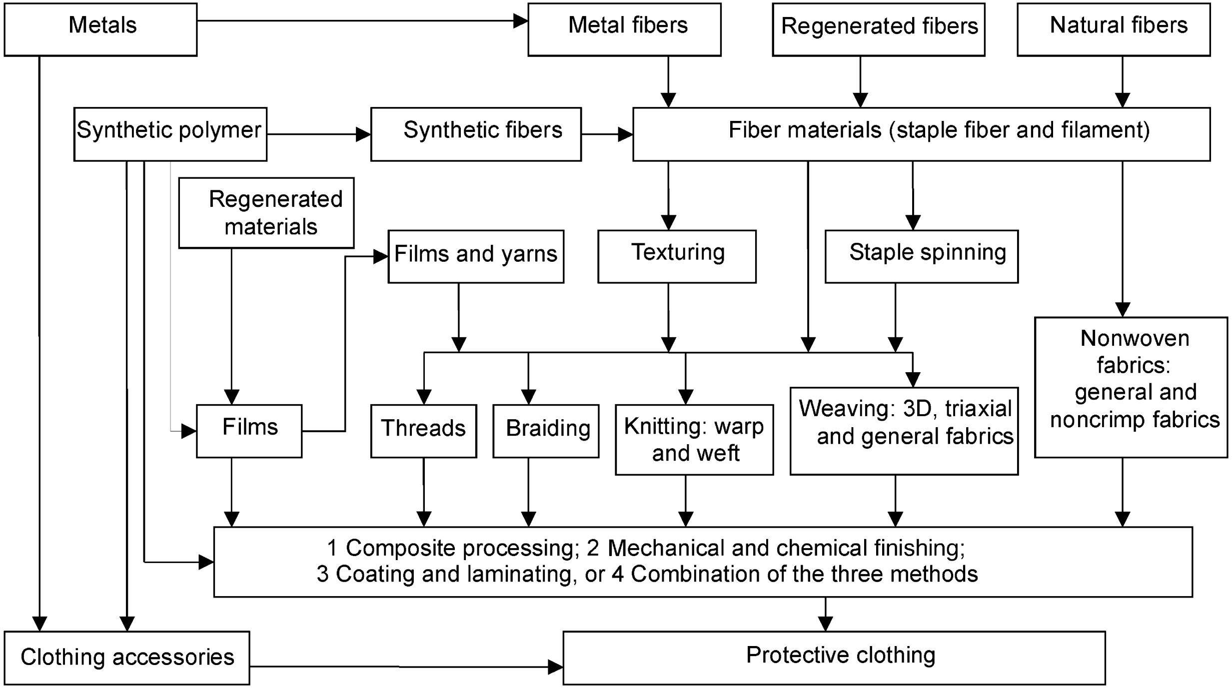
As discussed above, there exists a wide variety of personal protective clothing manufactured to suit a particular end use requirement. Protectivity can be imparted to clothing using standard textile manufacturing technologies or by any applicable new technologies. Except for a few items such as safety 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 $70\,\mathrm{GNm}^{-2}$ 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.

1.6 References

Abbott N J (2001), 'Coated fabrics for protective clothing', in Satas D and Tracton A A., *Coatings technology handbook* (2nd edn), Marcel Dekker, 819–823.

Adanur S (1995), *Wellington sears handbook of industrial textiles*, Lancaster, Pennsylvania, Technomic Publishing Company, Inc.

Anonymous (2003), 'Recommended practices for selection and use of surgical gowns and drapes', *Aorn journal*, 77(1), 206–210.

Bai J, Zeng X, Tanaka H and Zeng J (2004), 'Metallic single-walled silicon nanotube', *Proceedings of the national academy of sciences of the United States of America,* 101(9), 2664–2668.

Bajaj P, Sengupta A K and Tech B (1992), 'Protective clothing', *Textile progress*, 22(2/3/4), 1–117.

Barry J, Hill R, Brasser P, Sobera M, Keleijn C and Gibson P (2003), 'Computational fluid dynamic modeling of fabric systems for intelligent garment design', *MRS bulletin*, 28(8), 568–573.

Belkin N L (1999), 'Effect of laundering on the barrier properties of reusable surgical gown fabrics', *AJIC Am J Infect Control*, 27, 304–308.

Belkin N L (2002), 'A historical review of barrier materials', *Aorn journal*, 76(4), 648–653.

Bhat N V, Seshadri D T and Radhakrishnan S (2004), 'Preparation, characterization, and performance of conductive fabrics: Cotton + PANi', *Textiles Res J*, 74(2), 155–166.

Byrne C (2000), 'Technical textiles market – an overview', in Horrocks A R and Anand S C, *Handbook of technical textiles*, Cambridge, Woodhead, 462–489.

Canadian Institute of Child Health (1994), *The health of Canada's child A CICH profile*, 2nd edn.

Carroll T R (2001), 'Chemical protective clothing', *Occupational health & safety*, 70(8), 36–46.

Cheng K B and Lee M L (2001), 'Electromagnetic shielding effectiveness of stainless steel/polyester woven fabrics', *Textile Res J.*, 71(1), 42–49.

Cho J, Tanabe S and Cho G (1997), 'Thermal comfort properties of cotton and nonwoven surgical gowns with dual functional finish', *Journal of physiological anthropology*, 16(3), 87–95.

Choi H, Bide M, Phaneuf M, Quist and Logerfo F (2004a), 'Antibiotic treatment of silk produces novel infection-resistant biomaterials', *Textile Res. J.,* 74(4), 333–342.

Choi K, Cho G, Kim P and Cho C (2004b), 'Thermal storage/release and mechanical properties of phase change materials on polyester fabrics', *Textiles Res J.,* 74(4), 292–296.

Curtis K (1998), 'Infections in solid organ transplantation', *AJIC Am J Infect Control*, 26, 364–364.

Dalton A B, Collins S, Munoz E, Razal J M, Howard E, Ferraris J P, Coleman J N, Kim B G and Baughman R H (2003), 'Super-tough carbon-nanotube fibres', *Nature*, 423 (12), 703–703.

David Rigby Associates (2004), 'Technical textiles and nonwovens: World market forecasts to 2010', *www.davidrigbyassociates.com*

Doyle B (2000), 'Aramid, carbon, and PBO fibers/yarns in engineered fabrics or membranes', *Journal of industrial textiles*, 30(1), 42–49.

Elmi M, Kalliokoski P, Savolainen K and Kangas J (1998), 'Predictive pesticide exposure model and potato farming', *Occupational hygiene*, 4(3-6), 259–266.

Fan Q, Ugbolue S, Wilson A, Dar Y and Yang Y (2003), 'Nanoclay-modified polypropylene dyeable with acid and disperse dyes', *AATCC review*, 3(6), 25–28.

Fenske R A, Birnbaum S G, Methner M M, Lu C and Nigg H N (2002), 'Fluorescent tracer evaluation of chemical protective clothing during pesticide application in central Florida citrus groves', *Journal of agricultural safety and health*, 8(3), 319–331.

Fourt L and Hollies (1970), *Clothing comfort and function*, New York, Marcel Dekker, Inc.

Fung W (2000), 'Textiles in transportation', in Horrocks A R and Anand S C, *Handbook of technical textiles*, Cambridge, Woodhead, 490–528.

Gibson P, Schreuder-Gibson H and Rivin D (2001), 'Transport properties of porous membranes based on electrospun nanofibers', *Colloids and surfaces A: Physicochemical and engineering aspects*, 187–188, 469–481.

Gies P H, Roy C R, MeLennan A, Diffey B L, Pailthorpe M, Driscoll C, Whillock M, Mckinlay A F, Grainger K, Clark I and Sayre R M (1997), 'UV protection by clothing: An intercomparison of measurements and methods', *Health physics society*, 73 (3), 456–464.

Gies P H, Roy C R, Toomey S and Mclennan A (1998), 'protection against solar ultraviolet radiation', *Mutation research*, 422, 15–22.

Hall M E (2000a), 'Finishing of technical textiles', in Horrocks A R and Anand S C, *Handbook of technical textiles*, Woodhead, Cambridge.

Hall M E (2000b), 'Coating of technical textiles', in Horrocks A R and Anand S C, *Handbook of technical textiles*, Woodhead, Cambridge.

Hatch K L (2002), 'American standards for UV-protective textiles', *Recent results in cancer research*, 160, 42–47.

Hearle J W S, Hollick L and Wilson D K (2001), *Yarn texturing technology*, Woodhead, Cambridge.

Holme I, McIntyre J E and Shen Z J (1998), 'Electrostatic charging of textiles', *Textile Progress*, 28(1), 1–90.

Holmes D A (2000), 'Textiles for survival', in Horrocks A R and Anand S C, *Handbook of technical textiles*, Cambridge, Woodhead, 462–489.

Jacobs M J N and Van Dingenen J L J (2001), 'Ballistic protection mechanisms in personal armour', *Journal of materials science*, 36(13), 3137–3142.

Kasturiya N and Bhargava G S (2003), 'Liquid repellency and durability assessment: a quick technique', *Journal of industrial textiles*, 32(3), 187–222.

Kathirgamanathan P, Toohey M J, Haase J, Holdstock P, Laperre J and SchmeerpLioe G (2000), 'Measurements of incendivity of electrostatic discharges from textiles used in personal protective clothing', *Journal of electrostatics*, 49, 51–70.

Khakhar D V (1998), 'Manufacture of ultra high modulus polymer fibres: The polymerization step', *Journal of scientific & industrial research*, 57(8), 429–440.

Khokar N (2001), '3D-weaving: Theory and practice', *J. Text. Inst. (part 1),* 92 (2), 193–207.

King M W (1988), 'Thermal protective performance of single-layer and multiple-layer fabrics exposed to electrical flashovers', in ASTM STP 989, Mansdorf S Z, Sager R and Nielsen A P, *Performance of protective clothing: Second symposium,* American Society for Testing and Materials, Philadelphia.

Kirkpatrick S (1973), 'Percolation and conduction', *Rev. Mod. Phys.,* 45(4), 574.

Koscheyev V S and Leon G R (1997), 'Rescue worker and population protection in large-scale contamination disasters', *Clinical & health affairs*, 80(1), 23–27.

Krishnamoorti R, Vaia R A and Giannelis E P (1996), 'Structure and dynamics of polymer-layered silicate nanocomposites', *Chemical materials*, 8(8), 1728–1734.

Last B J and Thouless D J (1971), 'Percolation theory and electrical conductivity', *Phys. Rev. Lett.*, 27(25), 1719.

Leonas K K and Jinkins R (1997), 'The relationship of selected fabric characteristics and the barrier effectiveness of surgical gown fabrics', *AJIC Am J Infect Control*, 25, 16–23.

Mackay M and Scanlan A (2001), *Sports and recreation injury prevention strategies: Systematic review and best practices executive summary*, British Columbia injury research and prevention unit.

Mandel J H, Carr W, Hillmer T, Leonard P R, Halberg J U, Sanderson W T and Mandel J S (1996), 'Factors associated with safe use of agricultural pesticides in Minnesota', *The Journal of Rural Health*, 12(4), 301–310.

McLellan T M (1996), 'Heat strain while wearing the current Canadian or a new hot-weather French NBC protective clothing ensemble', *Aviation, space, and environmental medicine*, 67(11), 1057–1062.

McQueen R H, Laing R M, Niven B E and Webster J (2000), 'Revising the definition of satisfactory performance for chemical protection for agricultural workers', *Performance of protective clothing: Issues and priorities for the 21st century*, 7, 102–116.

Miraftab M (2000), 'Technical fiber', in Horrocks A R and Anand S C, *Handbook of technical textiles*, Woodhead, Cambridge.

Miyasaka K (1986), 'Mechanism of electrical conduction in electrically-conductive filler-polymer composites', *Int. Polym. Sci. Technol.,* 13(6), 41–48.

Morton W E and Hearle J W S (1997), *Physical properties of textile fibres*, The Textile Institute, UK.

Muza S R, Banderet L E and Forte V A (1996), 'Effects of chemical defense clothing and individual equipment on ventilatory function and subjective reaction', *Aviation, space, and environmental medicine*, 67(12), 1190–1197.

Ogin S L (2000), 'Textile-reinforced composite materials', in Horrocks A R and Anand S C, *Handbook of technical textiles*, Woodhead, Cambridge.

O'Mahony M and Braddock S E (2002), *Sporttech, revolutionary fabrics, fashion and design*, Thames & Hudson.

Osaki S (1996), 'Spider silk as mechanical lifeline', *Nature*, 384 (5), 419–419.

Panek C (1982), *Protective clothing*, Shirley Institute, Manchester.

Park J and Zellers E T (2000), 'Determination of solvents permeating through chemical protective clothing with a microsensor array', *J Enviro. Monit*, 2, 300–306.

Park S and Jayaraman S (2003), 'Smart textiles: Wearable electronic systems', *MRS bulletin*, 28(8), 585–590.

Patel S R, Urech D and Werner H P (1998), 'Surgical gowns and drapes into the 21st century', *Journal of theatre nursing*, 8(8), 27, 30–32, 34–27.

Pause B (2003), 'Nonwoven protective garments with thermo-regulating properties', *Journal of industrial textiles*, 33(2), 93–99.

Perepelkin K E (2001), 'Chemical fibers with specific properties for industrial application and personnel protection', *Journal of industrial textiles*, 31(2), 87–102.

Qian L (2004), 'Nanotechnology in textiles: Recent developments and future prospects', *AATCC review*, 4(5), 14–16.

Rajendran S and Anand S C (2002), 'Developments in medical textiles', Textile progress, 32(4), 1–42.

Reinert G, Fuso F, Hilfiker R and Schmidt E (1997), 'UV-protecting properties of textile fabrics and their improvement', *Textile chemist and colorist*, 29(12), 36–43.

Richardson J E and Capra M F (2001), 'Physiological responses of firefighters wearing level 3 chemical protective suits while working in controlled hot environments', *Journal of occupational and environmental medicine*, 43(12), 1064–1072.

Rissanen S and Rintamaki H (2000), ‘Prediction of duration limited exposure for participants wearing chemical protective clothing in the cold’, *International journal of occupational safety and ergonomics*, 6 (4), 451–461.

Road B (2001), ‘Technical fabric structures – 1. Woven fabric’, in Horrocks A R and Anand S C, *Handbook of technical textiles*, Woodhead, Cambridge.

Rohrlich S T and Rubin R W (1975), ‘Biochemical characterization of crystals from the dermal iridophores of a chameleon *Anolis carolinensis*’, *Journal of cell biology*, 66(3), 635–645.

Schreuder-Gibson H L, Truong Q, Walker J E, Owens J R, Wander J D and Jones W E Jr. (2003), ‘Chemical and biological protection and detection in fabrics for protective clothing’, *MRS bulletin*, 28(8), 574–578.

Scott R A (1981) ‘Static Electricity in Clothing & Textiles’ in Thirteenth Commonwealth Defence Conference on Operational Clothing & Combat Equipment (Malaysia) Colchester, UK, Stores & Clothing Research & Development Estab.

Scott R A (2000), ‘Textiles in defence’, in Horricks A R and Anand S C, *Handbook of technical textiles*, Cambridge, Woodhead.

Service R F (2002), ‘Mammalian cells spin a spidery new yarn’, *Science*, 295 (18), 419–421.

Shekar R I, Kasturiya N, Rajand H and Mathur G N (2001), ‘Studies on effect of water repellent treatment on flame retardant properties of fabric’, *Journal of industrial textiles*, 30(3), 222–253.

Singh O P and Kaur J (1997a), ‘Transmission, distribution and analysis of residual pesticides, and barrier and comfort performance of protective clothing: A review (Part I)’, *Textile dyer & printer*, (6), 14–16.

Singh O P and Kaur J (1997b), ‘Transmission, distribution and analysis of residual pesticides, and barrier and comfort performance of protective clothing: A review (Part II)’, *Textile dyer & printer*, (7), 11–13.

Smith B L, Schaffer T E, Viani M, Thompson J B, Frederick N A, Kindt J, Belcher A, Stucky G D, Morse D E and Hansma P K (1997), ‘Molecular mechanistic origin of the toughness of natural adhesives, fibers and composites’, *Nature*, 399(24), 761–763.

Smith P A (2000), ‘Technical fabric structure – 3. Nonwoven fabrics’, in Horrocks A R and Anand S C, *Handbook of technical textiles*, Woodhead, Cambridge.

Su C and Chern J (2004), ‘Effect of stainless steel-containing fabrics on electromagnetic shielding effectiveness’, *Textile Res J*, 74(1), 51–54.

Tanaka G and Goettler L A (2002), ‘Predicting the binding energy for nylon 6, 6/clay nanocomposites by molecular modeling’, *Polymer*, 43, 541–553.

Tortora P G (1978), *Understanding textiles*, Macmillan Publishing Co. Inc., New York.

Vahdat N and Sullivan V D (2001), ‘Estimation of permeation rate of chemicals through elastomeric materials’, *Journal of applied polymer science*, 79, 1265–1272.

Vigo T L (1983), ‘Protection of textiles from biological attack’, in Lewin M and Sello S B, *Chemical processing of fibers and fabrics, Functional finishes Part A*, 368–426.

Vo E, Berardinelli S P and Boeniger M (2001), ‘The use of 3M porous polymer extraction discs in assessing protective clothing chemical permeation’, *Applied occupational and environmental hygiene*, 16(7), 729–735.

Vollrath F and Knight D P (2001), ‘Liquid crystalline spinning of spider silk’, *Nature*, 410 (29), 541–548.

Voronkov M G, Chernov N F and Baigozhin A (1999), ‘Bioprotective heteroorganosilicon coatings’, *Journal of coated fabrics*, 19 (1), 75–87.

Wakelyn P J (1997), ‘Overview of cotton and flammability’, in Conference on recent advances in flame retardancy of polymeric materials: Materials, Applications, Industry developments, and market, *Recent advances in flame retardancy of polymeric materials*, Morwalk, CT: Business Communication, Co.

Wakelyn P J, Rearick W and Turner J (1998), ‘Cotton and flammability – overview of new developments’, *American dyestuff reporter*, 20(2), 13–21.

Wang S Q, Kopf A W, Marx J, Bogdan A, Polsky D and Bart R S (2001), ‘Reduction of ultraviolet transmission through cotton T-shirt fabrics with low ultraviolet protection by various laundering methods and dyeing: Clinical implications’, *J Am Acad Dermatol*, 44(5), 767–774.

Wasterlund D S (1998), ‘A review of heat stress research with application to forestry’, *Applied ergonomics*, 29 (3), 179–183.

Weinrotter K and Seidl S (1993), ‘High performance polyimide fibers’, in Lewin M, *High technology fibers Part C*, Brooklyn, New York.

Wilson M, Kannangara K, Smith G, Simmons M and Raguse B (2002), *Nanotechnology, Basic science and emerging technologies*, Chapman & Hall/CRC.

Wilusz E, Truong Q T, Rivin D and Kendrick C E (1997), ‘Development of selectively permeable membranes for chemical protective clothing’, *Polymeric materials science and engineering*, 77, 365–365.

Xin J H, Daoud W A and Kong Y Y (2004), ‘A new approach to UV-blocking treatment for cotton fabrics’, *Textile Res J,* 74(2), 97–100.

Zhang X and Raheel M (2003), ‘Statistical model for predicting pesticide penetration in woven fabrics used for chemical protective clothing’, *Bull Environ Contam Toxicol*, 70, 652–659.

Zi J, Yu X, Li Y, Hu X, Xu C, Wang C, Wang X, Liu X and Fu R (2003), ‘Coloration strategies in peacock feathers’, *Proceedings of the national academy of sciences of the United States of America*, 100 (22), 12576–12578.

Zins H M (1998), ‘Testing and evaluation of surgical gown fabrics: comments and concerns’, *AJIC Am J Infect Control*, 26, 364–365.

Fashion and function – factors affecting the design and use of protective clothing

3.1 Introduction

The design of protective clothing is a subject covering an extremely wide range of circumstances, as indicated by the breadth of activities and diverse contexts included in the present volume. The development of effective protective clothing products and systems is essential for the safe conduct of specifically identified activities spanning, for example: conventional and extreme sports, police and military operations, chemical, agricultural and industrial working, medical and surgical procedures, fire fighting and space exploration. Clothing fulfils a basic human need (Maslow, 1954, 1970), with normal everyday wear providing an acceptable level of protection from environmental and climatic conditions and importantly creating social acceptability. For more extreme conditions, further specific protection is required.

Textiles and clothing systems designed to protect from physiological discomfort have a long history, for example, from clothing designed to protect early motorists and pilots exposed in open vehicles and planes. The last century witnessed enormous developments in textile technology that were driven by the need to improve protective clothing, particularly for military and space applications. Rapid progress in textile development now offers enhanced functionality and responsiveness to changes in environmental conditions, and the recent development of 'smart' and 'intelligent' textiles is accelerating. The transition from natural materials to man-made and engineered high-performance textiles can be illustrated by a comparison between equipment taken on mountaineering expeditions during the 20th century: in the 1930s 'Grenfell' cotton cloth parkas with woollen fleece lining, wolverine fur hoods and three hand-knitted Shetland wool sweaters were worn to scale Nanda Devi; similarly in 1953 the Everest expedition team wore heavy layers of tweeds and string vest, wool shirt, two Shetland pullovers and two pairs of wool socks; in 1970 Chris Bonington took to Annapurna parkas made of 4 oz nylon with open cell foam liner, with bonnet of nylon lined with artificial fur and down-filled suits; by 1982 innovations in modern fibres and finishes, including brands such as Gore-tex®, Thinsulate® and synthetic insulations such as Hollofil®, enabled small teams to survive conditions which would have halted previous expeditions (McCann, 1999: 53, 61, 270).

This chapter examines the product development design process appropriate for protective clothing, the increasing synergy between fashion considerations and functional design and the reconciliation of factors which must be taken into account. It also illustrates some current examples of developments in protective clothing in relation to fashion, and future directions in textiles which will influence both protective clothing and fashion.

3.2 Factors influencing the design development process

The range of hazards to be dealt with by the vulnerable human occupants of protective clothing can be broadly classified into chemical, thermal, mechanical, biological and nuclear or other forms of radiation (Raheel, 1994:1), and include both civilian and military situations. The level of protection required varies enormously within and between each of these categories and is one of the first factors to be determined when responding to a design request. For example, protection may be required from extremes of hot and cold weather, dirt, chemical spillages, fire, bullets, cuts, impact and abrasion, together with safety considerations including visibility and personal protection. Other major factors include the consideration of the entire clothing system in use, the specific functional requirements and the optimising of all components when working together to enable the activity to be successfully carried out whilst maximising protection and eliminating or minimising risk. The notion of fashion and aesthetics in such a context may be deemed by some to be superficial, however, in order to be acceptable to the user, the clothing must balance functional factors with both structural design and aesthetic considerations, including the important subjective element of comfort. Indeed, it is possible for a perfectly functional protective garment to be rejected on the grounds of appearance or perceived discomfort, putting the potential user at risk.

3.2.1 Fashion

In the latter half of the 20th century, fashion has played an increasingly important role in the lifestyle of a wide range of social groups and spread far beyond elitism and the early ‘trickle-down’ theories of fashion dissemination (Simmel’s theory of the fashion process summarised as a cycle of ‘adoption, imitation and abandonment’ by Sweetman (2001: 61); see also Entwistle (2000)) to a number of other industries, such as the automotive and electronics industries. Since the 1990s, designer-led high fashion has become democratised and some formerly exclusive and aspirational luxury brands (e.g. Gucci, Armani, Burberry) have become widely available. Promotional campaigns and global marketing have played their part in the accessibility and spread of awareness of design and aesthetic considerations in both men's and women's clothing from high street to couture level. At the same time, casual clothing has seen a growing influence from active sportswear and youth culture permeating its design, including the increased use of technical fabrics which were first developed for specific protective needs. Conversely, there is a higher expectation of performance, comfort and durability of textiles used in casual clothing.

Fashion operates on many levels from subtle to extreme. Even uniforms can be subtly customised, showing the desire for individual identity and expression. In her essay *The Dressed Body* cultural theorist Entwistle (2001: 48) argues 'dress is part of the micro-order of social interaction and intimately connected to our (rather fragile) sense of self which is, in turn, threatened if we fail to conform to the standards governing a particular social situation. Dress is therefore a crucial dimension in the articulation of personal identity'. As identified by Joseph (1986: 144) 'While the utilitarian aspect of occupational clothing is undeniably of great importance, nevertheless, it is only one of many functions served by such clothing.' Clothing can represent emotional aspects of behaviour through cultural and peer identification, and use of colour and style. Appropriate clothing engenders and enhances social acceptance and self esteem, which, when coupled with confidence in a product's functionality, will enhance wellbeing, personal confidence and performance productivity in specific working circumstances.

Military and other public service personnel such as fire-fighters and police wear modern branded sportswear for off-duty activities, which they find to be comfortable, practical and fashionable, and are now demanding similar styling together with functionality for their work-based clothing, to improve flexibility and manoeuvrability whilst performing tasks. Military uniforms are not updated very often, and government issue is sometimes substituted by branded sportswear purchases, which although better in fabric quality and comfort, do not necessarily meet all the functionality standards. Referring to motorcyclist's clothing choices in the Metropolitan Police, the technical support manager states:

> Reputation, brand names, features, etc., can form the basis for their selection. The Met issues motorcycle jackets, which have been tested to a very high level. To comply, the jackets are lined with a denser interlining, making the jacket less comfortable (heat retention) than jackets available on the commercial market. The staff does not always appreciate this fact and criticism of 'the Met always provides a cheap option' or even 'an inferior product' is regularly voiced.

Soldiers have also criticised their current clothing from the point of view of comfort, and many remove the protective linings of their jackets because they are too stiff, or buy their own in the retail market, reducing effective protection (authors' interviews, M Campbell, Woolmark Company; R Allen, Shapeanalysis; R von Szaley Metropolitan Police, 2005).

The extent to which fashion considerations impact on the use of protective clothing is clearly dependent on the context of the actual function being carried out. In the case of military or civilian personnel in life-threatening situations, there is no real place for aesthetic considerations, however, the same personnel may be prepared to relax their approach to the complete clothing system when in a non-threatening or routine circumstance, with potentially dangerous consequences. According to the technical support officer of the Metropolitan Police uniform services, 'image is important as it can influence the wearer's perceptions of comfort. Users consider themselves 'specialists in the field'. However, they are strongly influenced by brands and labels. They make choices defying technical advice based on perceived quality advantages. Some manufacturers are well aware of this fact and design accordingly' (author interview R von Szaley). Balancing the range of design requirements across function, performance, protection, comfort and fashion will be discussed in the next section.

3.2.2 Functional design and fashion design

A successful design comprises many elements, and in the case of protective clothing must meet stringent functional requirements and conform to regulatory standards for the specific industry. 'Good' design must have the following properties in this context:

- meets functional requirements
- is appropriate for task and aesthetically pleasing
- is fit for purpose, durable and performs to or exceeds required standards
- is acceptable to both the user and the client (or other interested party) with respect to culture, traditions, specification, manufacturing and costs.

It may, in addition, have the following characteristics, which mark out the best design solutions:

- provides an innovative solution which simplifies existing products, extends norms or breaks new ground in materials, manufacturing or design concept
- adds value by exceeding specifications in functionality, ergonomics, ease of use or other aspect

whereas 'bad' design would clearly fail to meet some of the first set of criteria, and may also possess or produce unwanted characteristics, such as moisture retention, or annoying details which deter use. It would therefore never deliver the additional benefits mentioned above.

Fashion considerations within the design process, including tangible and more intuitive aspects, can be summarised as follows:

- self-perception and identity
- cultural identification with recognisable social groups
- fashion currency; awareness of relevant fashion and lifestyle trends
- feelings and emotions including comfort and wellbeing
- tradition and innovation – impact of emerging technological and fabric trends
- appropriate form, style, materials and colour (overall concept and silhouette)
- market level and costings
- cut, style and proportion (i.e. not 'old-fashioned')
- manufacturing processes and detailing
- functional and fit for purpose
- choice and range availability.

Various models of the design process have been developed in different contexts, particularly in generic product development (see Section 3.2.4). Few, however, relate to fashion or clothing design specifically (although Pitimaneeyakul *et al.* (2004: 119) propose a model specifically for knitwear development; Lamb and Kallal (1992: 42) presented a conceptual framework for apparel design), and still fewer are offered within protective clothing design (see Watkins (1995: 334) and Raheel (1994: 25)). Much of the focus is on the initial stages of ideation and the models do not develop detailed design criteria. However, McCann (1999) focused specifically on the design requirements for performance sportswear which developed a more detailed and balanced approach, integrating performance and fashion.

Fashion and apparel designers operate in a variety of markets, from mass market to high fashion and designer brand level, or may work with individual clients in the couture or bespoke areas of the industry. This spectrum is reflected in both the volume of garments produced and their related cost bracket, and supply-chain logistics mean the smaller the number produced, the higher the cost. The textile, fashion and clothing industries are a significant global economic force. The fashion industry is well known for being fast-moving in terms of both design and intensive production cycles. This has been accentuated by recent trends towards accelerated cycles and the further compression of time to market, resulting in a new mass market category 'fast fashion', which operates on a turn around of between six to eight weeks, rather than the traditional norm of three to six months.

The fashion design process is initiated by an external brief or by the regular imperative for a new collection stimulated by the fashion seasonal cycles, and is researched within and supported by an international network of trade shows for trends, yarns, fabrics, clothing and high-profile designer fashion catwalk presentations, which traditionally provide 'inspiration' for the high street levels of the market, although the flow of ideas now also works in the opposite direction, from 'streetwear' to designer level. There has in recent years been a polarisation in the marketplace to designer branded goods at one extreme and low priced commodity clothing such as t-shirts, jeans and basic wear at the other, which has seen, particularly in the UK, the retraction of the middle level of the market. At the same time, sportswear has grown in influence and particularly sports footwear brands, such as Nike, have developed as a fashion offering, and certain items of clothing, like the baseball cap, the football shirt, and the trainer, have become iconic and significant symbols of consumer culture. To come full circle, several popular sportswear brands and high street retailers have recently collaborated with high-profile designer names, e.g., Adidas and Yohji Yamamoto; Marks & Spencer and Betty Jackson; Debenhams and John Rocha; Vexed Generation and Puma, Hennes & Mauritz and Karl Lagerfeld.

Watkins (1995) differentiates between the normal processes of clothing and fashion design and the ‘functional design’ process necessary to achieve the rigorous solutions often required for protective clothing. This is distinguished by an intensive and in-depth period of evaluation of the users needs, involving methodologies including direct observation, interviews and technical testing.

3.2.3 Design process model for the development of protective clothing

Conceptual representations of the product development process have been proposed by several authors, including Carr and Pomeroy (1992) and Lamb and Kallal (1992); a range of features can be identified which are represented in Fig. 3.1 as a cycle of stages.

Problem exploration and analysis

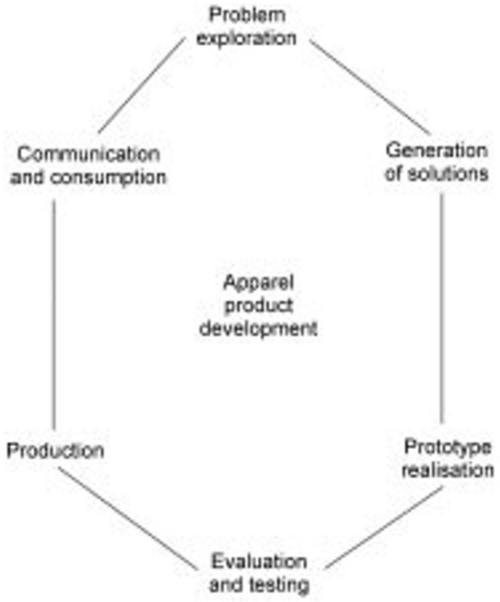
This is the starting point where the characteristics required of the new protective product and its specialised design brief is determined. These break down into four categories: the type of user requiring protection; the activity with which the user is to engage; legislation and standards governing protective clothing, with special reference to the circumstances under consideration; the protective product.

The user

The gender, age, size, shape, lifestyle and socio-economic group of the proposed user group are required, plus an analysis of their clothing preferences. This data may be gathered through interviews, direct and indirect observation and questionnaires.

The activity

Analysis of the activity with which the user will engage is essential to be determined prior to the analysis of the product. Ergonomic and physiological



3.1 The process of apparel product development (Source: J Bougourd).

issues, such as range of movement, temperature variations or specific medical condition may be among the intrinsic requirements, whilst extrinsic factors will comprise the environment within which the activity is to be undertaken, and the hazards encountered. The design must meet the challenges encountered in particular occupational activities, and the impact of environmental factors such as airflow, extreme cold or a range of chemical hazards.

Legislation and standards

A review of British, European and international standards for body and product sizing, material testing, garment manufacture and product labelling would need to be undertaken to establish a set of criteria forming the design envelope. For example, the fire-fighters' tunic (section 3.4.2) must conform to standard EN 469, and the fluorocarbon chemical protection fabric coating to EN368. New materials may require the development or adaptation of existing textile testing or new tests and garment manufacturing procedures, prior to their use. For example, textiles incorporating new applications of nanotechnology in coatings may have little previous history and need to be evaluated independently and in context.

The protective apparel product

The investigation may include three aspects: review of earlier products and clothing systems; an analysis of and comparison between existing products and systems; and identification of new and emerging product components. A review of previous products provides an opportunity to identify and evaluate the process followed in reaching previous design solutions. (It would, however, be expected that technological advances – particularly in materials and product components – would now need to meet a wider range of environmental conditions and standards.) Existing products may either be those of competitors and/or drawn from an in-house range. The criteria assembled from the user group and activity analysis determine the level of protection required and the context the apparel is worn in, plus any negative characteristics to be eliminated. The outcome of this stage enables successful product and system characteristics to be identified.

The compilation and comparison of initial information comprises: user profiles; product price, size and colour ranges; new and existing materials, thread and fastening components; manufacturing processes; garment labelling/aftercare; fashion and design content. Based on research at trade fairs and sampling, a comprehensive study of contemporary fashion, colour, texture, line and silhouette trends, and relevant cultural contexts, informs the final selection of product characteristics, both functional and aesthetic. For example, outdoor clothing company Rohan believe that form still follows function, but that protective clothing must have a design element. Working two years ahead of the retail season, they research and monitor fashion predictions and trends, particularly in materials, and have recently introduced a 10% natural fibres component into their synthetic fabrics for improved drape and handle. They developed their ‘baggy’ trousers silhouette in response to fashion research, and more ‘technology’, i.e., functionality is being built into the outer fabric layer (author’s interview J. Donaldson).

Outcomes – the design brief

The final outcome of problem exploration and analysis is the design brief. The brief profiles the user group – age, size, shape, culture, lifestyle – from which a body size chart, shape profile and appropriate body form or block pattern can be selected or created. The outcomes of the activity analysis define ranges of movement required whilst wearing the clothing, anthropometric measurements indicate any increases or decreases in body size and shape from which an amended size chart, shape profile and block patterns can be produced. The physiological changes experienced when carrying out the activity will be identified and the range of environmental conditions determined.

The type of product must be appropriate to the activity; for example, whether separate single items such as jackets or trousers, or whole body coverings and consideration of the entire system of clothing and its possible interactions. The ease of putting on and taking off the garments is a crucial consideration for certain activities such as emergency services. A cost price range will be specified for each of the products, which in turn determines the choice of potential components and manufacturing processes. The product components – materials (fibres, fabric constructions and finishes), fastenings and closures – will be selected to be appropriate to the activity, test results, price range, and fashion trends. Manufacturing processes, i.e., whether sewn, bonded or welded, or used in combination, must be determined and will be considered in relation to the activity (the range of movement and environmental conditions), materials (fibres, woven, knitted or non-woven fabrics, and finishes) and aftercare requirements (e.g. whether wash or clean or disposable). The outcomes of the fashion trend analysis will inform material and component selection – colour, texture, line, and silhouette, and influence the overall design concept and the development of individual design elements (e.g. pockets and details). As previously indicated, the culture of the activity and its traditions will have a bearing on design selection and acceptability by the user group.

Generation of solutions

Potential solutions will next be developed using two and three-dimensional visualisations, including both manual sketching and computer-aided design programmes, supported by experimental design developments in which new elements are introduced and variations applied. This is a crucial stage in which innovations can be introduced, and where an open design brief which is more contextually and ergonomically oriented can generate new solutions, as one too narrowly specified will result in only incremental solutions. An evaluation and selection of proposed designs will be made after this stage, which may have several iterations, to ensure the fit to the design brief and suitability of the manufacturing processes specified and that the solution falls within the proposed cost range

Prototype realisation

Preparation for manufacturing the prototype includes the assembly of a modified size chart, shape profile and block pattern incorporating the age and size range of the user group, the range of movement identified in the activity analysis and the product type. These items, together with an appropriate body form and an analytical drawing, will be used to produce the prototype pattern, manufacturing specifications, three-dimensional sample products and full material and manufacturing costing.

Evaluation and testing

The range of products will be evaluated and tested against the set of criteria identified in the design brief, preferably by trials with the user group. A full functional analysis is undertaken and – according to the results – is revised and re-evaluated before a range is selected for production. Graded patterns, garments and final costings will then be produced and evaluated.

Production

In preparation for production the following will be provided: labour and material costings, together with appropriate markers; full base materials and component specifications; garment size and manufacturing specifications, with directions for the colour and size apportionments; labelling and packaging details. Those specifications will be used to monitor the quality of the merchandise throughout the production process, (cutting, manufacturing, finishing, pressing and packaging) in accordance with the schedule.

Communication and consumption

It is important that evaluation continues as the product becomes available to the user group. Observation, monitoring and analysis of the users' responses, preferences and feedback is essential to continue the fine tuning of the designs, including evaluation of the performance of individual products within the entire clothing system, their durability and any unforeseen problems in performance. This information can be fed incrementally into the renewal programme, so that enhancement is continuous. Some of the products designed for protective clothing may enter the mainstream market and evaluation can be conducted within the commercial retail environment at various market levels.

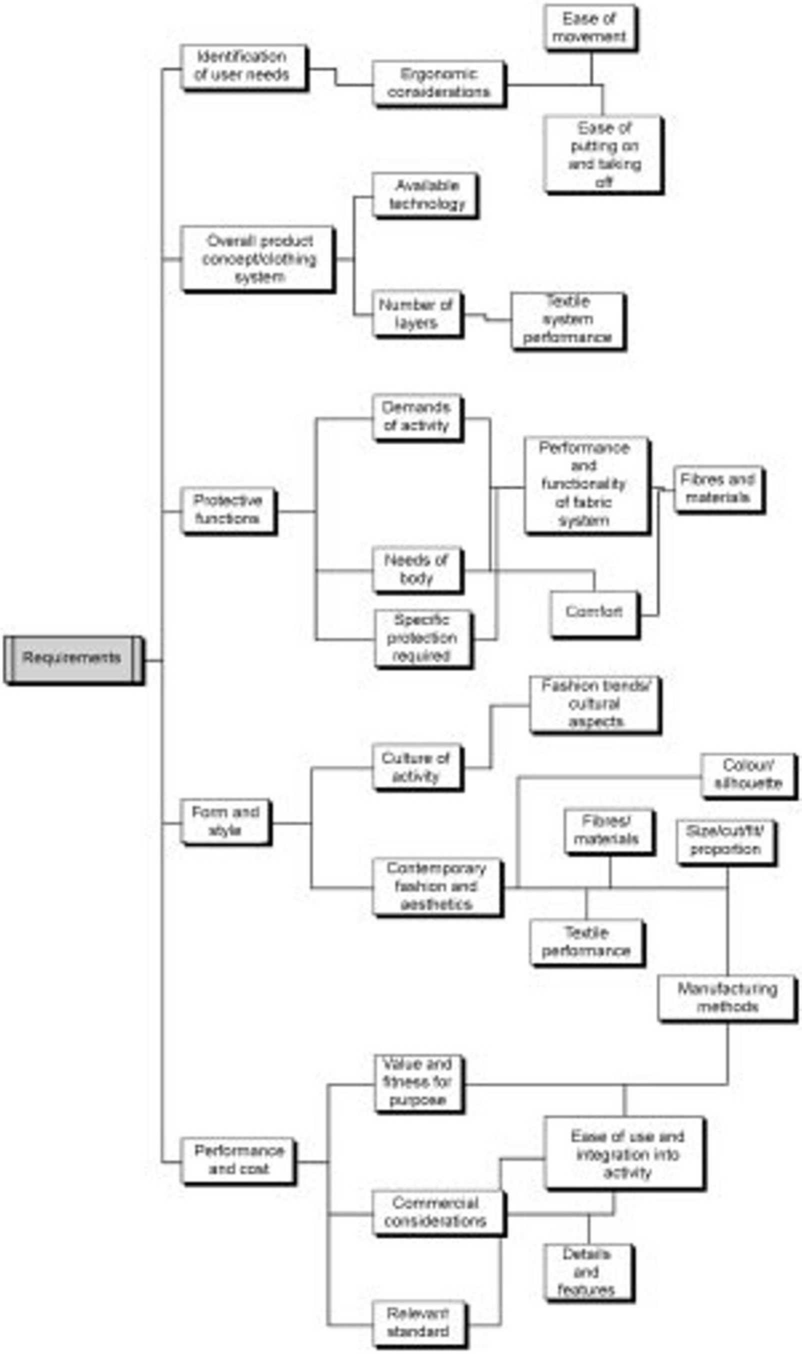
3.2.4 Tree of functional design requirements

To aid navigation through the complexity of choices and decisions to be made, the parameters of the design process can be represented as a 'tree' of requirements, which demonstrates the primary and secondary factors for consideration together with an increasing number of detailed sub-choices and issues which need to be taken into account, as outlined in the previous section and in Fig. 3.2. This method is adapted from McCann (1999). The primary factors are

- identification of users' needs and context
- overall product concept – clothing system: collective operation, number of layers, equipment and weight
- protective functions
- form and style
- performance and cost.

These primary factors can be further subdivided as:

- protective function – demands of the activity/needs of the body/specific protection required



3.2 Tree of requirements in the design development of protective clothing (Source: S Black and V Kapsali).

- form and style – culture of the activity/contemporary fashion and aesthetics
- performance and cost – relevant standards/commercial considerations and value/fit for purpose.

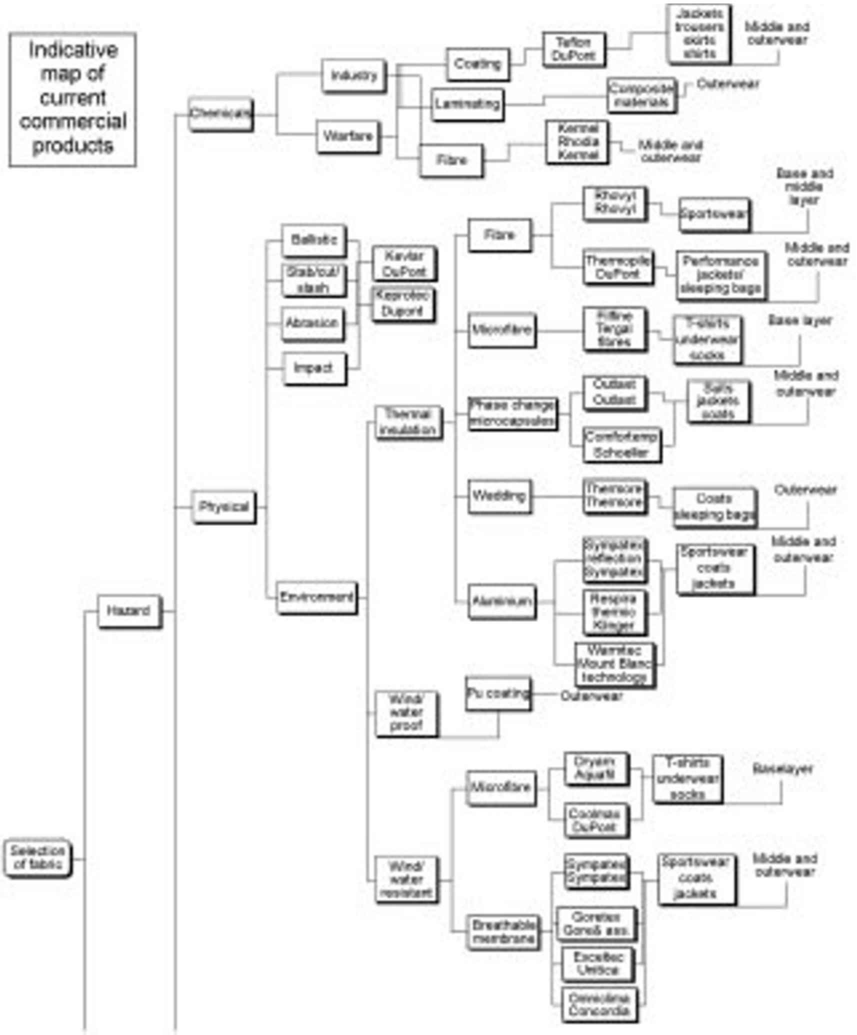
Taking the contemporary fashion and aesthetics requirement further will include aspects of fibres, materials, colour, functionality, fabric performance, size, silhouette, cut, fit, proportion, comfort, manufacturing methods, in addition to the fashion trends and cultural factors. As progress is made, this branch begins to overlap and converge with aspects of other branches of the tree, such as performance and ergonomics and the needs of the body. Some of the considerations and choices which have to be made include

- garment system – form of overall collective, base, mid or outer layer?
- fabric system performance and functionality – e.g., strength/water permeable or barrier/ insulating or conductive/weight to bulk, i.e., density/stretch or rigid/wicking properties
- fibre and fabric construction: natural/synthetic/blends; woven/knit/nonwoven/composite/single or bicomponent fibres/single or layered fabric elements
- aesthetic elements: colour/appearance/handle/touch/comfort on skin
- manufacturing processes: stitching/ bonding/moulding/welding/taping
- ease of putting on and taking off: openings and fastening systems/speed of operation
- details and features: pockets/attachments/accessories
- style/cut/fit/ease of movement.

Despite the complexity of the above requirements, the successful design and product development solution balances the primary factors through consideration of the sub-factors in such a manner as to arrive at a solution which meets the design brief to the required cost parameters and satisfies the key physical, social, psychological and aesthetic needs to combine protection, performance and fashion. However, one of the key inhibiting factors to the ideal design solution is often cost, therefore maximising the effectiveness of a clothing system for the available budget is a key skill practised by designers.

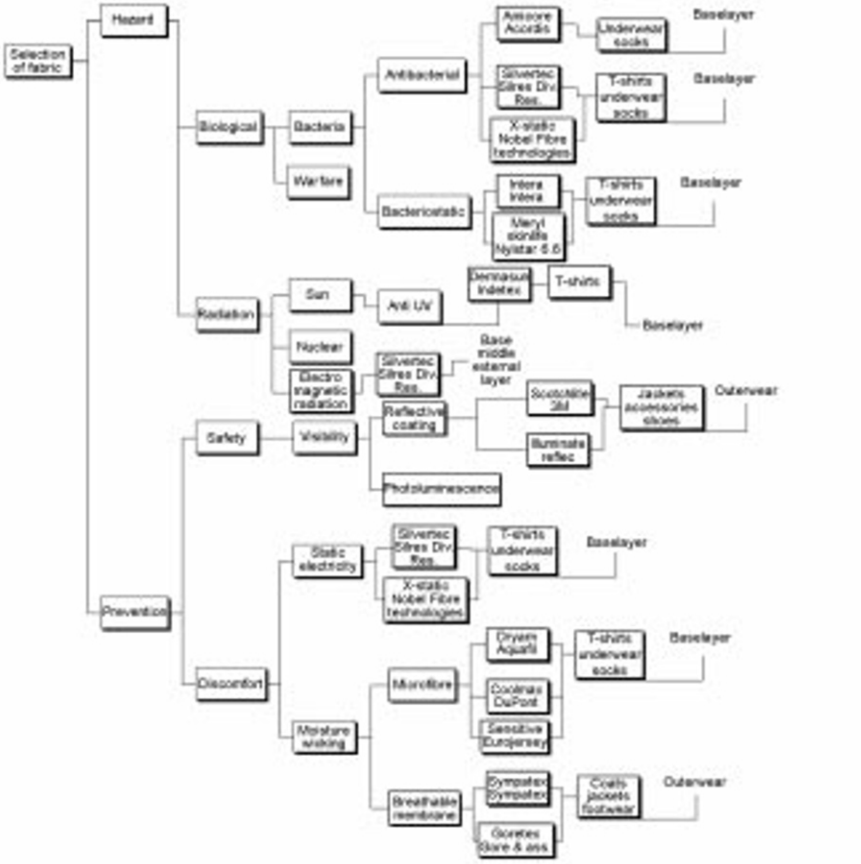
3.2.5 Selection of fabrics for protection

There is a bewildering array of possibilities when selecting textiles for protection, with many new and established fabrics available, some generic and others commercially branded. The mapping in Fig. 3.3 illustrates some of the fabric performance categories and examples of commercial products which are currently on the market. This map is indicative and not exhaustive, it illustrates the process of fabric selection from the initial stages of the design development where the requirements are being formulated to the final choice of fabric, which



3.3 Selection of fabric functionalities (Source: V Kapsali).

may be an existing product or a tailored functionality. Many of the readily available protective textiles, such as those sourced at fashion industry trade fairs (e.g. Premiere Vision in Paris) are those with functionalities that protect the user from physiological hazards, such as UV rays and the build up of bacteria within a clothing system. Other fabrics are sourced from specific specialist suppliers. Each function incorporated into a clothing system is in danger of being disabled unless careful consideration is given to the compatibility of each component at the beginning of the process.



3.3 Continued

3.3 Clothing systems and functionality

3.3.1 Clothing systems and protection

In a sociological reading, clothing is 'a system of signs that derives meaning from its context while enabling us to carry on our activities' (Joseph, 1986). The process of dressing is a ritual activity executed at various levels of consciousness and performed daily by each individual in preparation for social engagement. Items of apparel are selected and combined to create a 'system of clothing' generally composed of base, middle, and outer garment layers. This complex architecture of materials and the pockets of air contained within both the fabrics and garment structures extends from the skin's surface through all levels to the outer face of the fabric comprising the external layer of clothing. This system possesses a dynamic microclimate resulting from a variety of external factors such as the activity of the individual (which generates heat and moisture), and the climate of the immediate environment, and from internal factors such as the types of fibres, the structure of the textiles, the properties of the materials employed as well as the design of each garment. It is therefore evident that every component operates within a dynamic system of inter-relationships and the properties of any individual textile or functional design feature are subsumed and may be lost within the complexity of the collective clothing system, unless it is designed to work in an integrated manner (Renbourn, 1971).

In the field of protective clothing, systems are engineered to shield the wearer from hazards such as extreme environmental conditions, chemicals, fire, etc. Their aim is to enable the user to perform tasks in these conditions without endangering the wearer's health or well-being. Successful design is paramount and can affect the survival of the wearer in extreme conditions. Although protective clothing is designed to enhance the user's comfort and safety, if the system is not carefully engineered it can have a negative effect on the wearer's performance by causing heat stress and discomfort, reducing task efficiency and restricting the range of motion. These factors may cause the user to reject the protective clothing and thus increasing the risk of injury or disease (Adams *et al.*, 1994).

The success or failure of each clothing system cannot be measured by the performance of each of its parts individually but in the efficiency in which the components operate within a collective. In *A quest for thermophysiological comfort*, Brownless *et al.* reviewed the concept of physiological comfort in terms of technological efforts to improve the comfort sensation by developing wicking and insulation properties in textiles. The key observation made was that previous research in the area had misconstrued the concept of comfort in fabric requirements, resulting in the development of highly wicking and insulating textiles, which in extreme cases can lead to dehydration. The authors' findings highlight that 'a comfortable fabric is one which is not necessarily highly wicking or strongly thermally insulating, but one which has these two factors finely balanced in order to aid thermoregulation' (Brownless *et al.*, 1995).

Firefighters' uniforms must act as a barrier between the user and radiant heat from fire; they therefore need to insulate the wearer from intense heat. In 2003 Bristol Uniforms, supplier of protective clothing systems to the fire-fighting industry, commissioned physiology consultancy Human Vertex to investigate the effects of heat stress in existing uniforms and used serving firefighters as volunteers. The results highlighted that existing test methods used for the assessment of ergonomic and thermal effects of the clothing systems actually underestimated the impact of heat stress on the volunteers. Firefighters on duty mostly operate below their individual anaerobic threshold and the assumption has been that they should be able to perform in these circumstances for extended periods ('Out of the hot ashes', *Company Clothing*, July 2004, p28). Because the firefighters' garment systems are designed to have high levels of insulation, on one hand the user is protected from the external heat generated by flames, however, the internal heat generated from the movements in addition to being in a very hot environment remains within the system of clothing, this increases the intensity of the exercise, resulting in the firefighter becoming exhausted more quickly and not being able to perform for extended periods. (See also chapter 22 by Mäkinen.)

Other factors that affect the success of a protective clothing system are users' attitudes and beliefs. In a study of Alberta farmers focusing on their attitude towards the use of disposable protective coveralls during exposure to pesticides, it was found that the system was being rejected on the premise that it was perceived to be costly; further analysis revealed that the users had misconceptions about the necessity of the level of protection, and placed comfort and convenience at a higher priority (Perkins *et al.*, 1992). When the functionality of the garment system is not transparent to the target user, such as in the case of the Alberta farmers, the users can be deterred from integrating the protective clothing system as a necessary tool into their particular industry.

In industries where wearers are reliant on their clothing systems, users can become attached to certain products and tend to reject new developments. For example, a clothing system for cold-storage workers recently underwent a change ('Glacial shift', *Company Clothing*, July 2004). In this particular situation, thinner insulation was introduced into the system replacing the thicker counterpart, although the new insulation is equally as effective yet lighter, enhancing mobility of the user. It appeared that the target user in this situation failed to accept the new insulation because of their attitudes and beliefs; they were not convinced that the new types of insulation had equal performance although less bulk, and therefore rejected the new system. A designer must ensure the traditions and culture of the relevant industry or occupation are taken into account before proposing radical design solutions, and consider the information which must accompany any major change.

Aesthetic design can affect the success or failure of a clothing system through the way it makes the user feel, allows for personal expression, and generally enables the psychological functions of clothing, but there is very little research on this particular area. However, evidence is growing that fashionability affects the way protective clothing is perceived. For example, health care workers in Belgium and Holland found the garments they used for work boring and basic, so Belgium healthcare supplier Sacro introduced 'denim look' textiles into the garments in their range, which are now being used as part of the clothing systems in major hospitals in Antwerp, Brussels and Ghent ('Denim look hits healthcare', *Company Clothing*, July 2004, p32). Although there is no substantial evidence due to lack of research in the area, this article suggest that design and aesthetics can influence the attitude and possibly the performance of the user, through increased self-esteem. (Similarly, in a medical context, when researcher Rebecca Earley from Chelsea College of Art and Design recently designed a range of printed medical gowns for patients following operations, this was seen to enhance their self-esteem and aided recovery.) This is indicative of a growing trend towards both higher aesthetic and performance characteristics in everyday clothing, which has changed at a faster pace than the equivalents in corporate and protective clothing, creating a gap of expectations and usage between workers' on- and off-duty clothes. Off-duty clothes are more fashion conscious and can provide a higher level of social acceptability than many occupational working clothes.

Performance clothing is a testing ground for new innovations due to the demanding nature of the functionalities required from the systems; often technology transfer from other fields such as space exploration and aviation is introduced. However, innovation and practicality do not always go hand in hand. For example, electrically heated gloves were introduced to cold-storage workers who rejected them because they were expensive and the battery pack necessary for powering the function was too heavy ('Glacial shift', *Company Clothing*, July 2004).

3.3.2 System anatomy

The composition of a system of clothing can vary from a single garment or layer to multiple layers expanding outward from the skin. There are however three fundamental strata: a base layer, middle and external layer. Each stratum performs a range of basic operations; in protective garment systems additional functionality is usually incorporated at the middle and external level. However, a system of clothing does not operate as an individual entity, but in a dynamic relationship with the wearer, activity and environment. There may be choice in whether certain layers are worn, or different ways of configuring the system according to particular circumstances and need.

Base layer

The base layer lies on the surface of the skin and remains in direct contact with the body, therefore the fibres used in the garments need to be soft and smooth, while the textile system needs to be able to wick moisture away and insulate the body without restricting the wearer's movement. This can be engineered through combinations of fibre choice with woven or knitted structures that channel moisture away from the skin and towards the outer surface for evaporation. Base layer items are intimate underwear, vests, t-shirts, socks, sportswear or swimming costumes, this being a vital layer for comfort and insulation. The traditional 'string vest' was designed to trap as much air as possible, but is now considered old fashioned. Knitted textile structures are almost universally used in base layer garments for their inherent stretch properties ensuring the wearer ease of movement and flexibility without chafing. Additional functionalities such as antibacterial properties can also be introduced into base layer garments through specialised treatment of the fibres and textiles; this technology prevents the development of bacteria in base layer garments, thus managing the development of body odours, particularly used in socks.

Physiological comfort is possibly the most important functionality for this layer to operate successfully within a system. Physiological comfort from clothing can be highly subjective, and is in fact the attainment of a neutral sensation, which can be described as a state in which we are physiologically and psychologically unaware of the clothing we are wearing (Smith, 1993). In contrast, any sensations actually experienced indicate various levels of discomfort.

One of the parameters that influences discomfort is the system's ability to manage the air enclosed within its constructs, in particular the ability to wick moisture vapour through its strata. It is when the moisture emitted from the skin begins to saturate the base layer garments that the wearer begins to experience discomfort. Traditionally, cotton fibres have been employed, as they are naturally soft and absorbent, but cotton fibres have poor wicking ability, whereas historically underwear used woollen knit fabrics which provided absorbency and wicking, and wool is currently being re-introduced in yarn blends.

Cotton is widely used in base layer garments, although it is not the most functional of the natural fibres for thermal protection. During the 2004 annual Survival Conference, (Leeds UK) a new concept for a base layer garment was presented (Ellis and Brook, 2004). Manchester firefighters were experiencing problems during the summer months, when extinguishing wild land fires. Firefighters would not use any of the upper middle and external layers of their clothing systems, because of the heat, and would extinguish the fires dressed only in their cotton t-shirts. (See Fig. 3.4: Manchester Fire Brigade uniform.) The problem that emerged was that the hot embers produced by the wild land fires would burn holes in the firefighters' t-shirts. The collaboration between the Manchester Fire Service, Leeds University and Bolton Institute resulted in the development of a double jersey knitted garment using a 20% wool and 80% polyester blend yarn named Sportwool® by The Woolmark Company. T-shirts made from Sportwool, utilising the natural absorbency and vapour transportation of the wool component, were shown to have a range of functionalities superior to their cotton or 100% polyester counterparts. During the testing and wearer trials, Sportwool t-shirts proved to have an increased wicking ability, resistance to ember burns (due to the natural flame resistance of the wool and polyester fibres), and were considered more comfortable by the firefighters. Unsolicited testimonials confirm this fibre blend's enhanced comfort in other circumstances such as cycling (see, for example, www. teamestrogen).

Single-layer clothing systems such as swimsuits belong to the base layer category, the system being comprised of the swimmer, the suit, and the water. During the activity of swimming, the suit needs to stay firmly in place next to the body but when out of the water the suit needs to dry quickly in order for the system to be successful and not cause the user discomfort. Early swimming

3.4 Layers of firefighter's uniform, Greater Manchester Fire service (Source: K Whitehead).

costumes were made of knitted wool, to take advantage of the latent heat emitted on evaporation of water which reduced the wind chill effect, but manufacturers failed to recognise that they would also sag due to the weight of water absorbed. Speedo were the first to introduce the 'racing back' cutaway design in 1927 to reduce drag in the water (McCann 1999), a functionality which they recently introduced into the intrinsic structure of the textile employed by the system. Of biomimetic inspiration, this textile was initially designed for Olympic competitors, to imitate the structure of sharkskin, which has remarkable ability to minimise drag when swimming in the water. The interpretation has been achieved through the engineering of dermal denticles which are small hydrofoils having V-shaped ridges which decrease drag and turbulence. A more recent development is Aquablade® which uses stripes to create a channelling effect to move water across the body (source http://www.speedo.com/). Similarly, Jetconcept® by Adidas uses V-shaped ridges to reduce drag in the water and was worn by Ian Thorp in the 2004 Athens Olympics ('Jet Stream', *Textile Horizons*, p17, Sept–Oct 2004).

Mid-layer

The middle layer is positioned above the base layer but can also have areas that are in direct contact with the skin. Middle layer garments need to be durable, wicking, provide insulation, and ease of movement in a similar manner to the base layer. Additional protective functions can also be introduced at this level ranging from stain resistance to stab and ballistic protection, however this stratum begins to carry aesthetic values that communicate and socialise the body. Garments at this level can be upper bodywear items such as shirts, blouses, sweaters, fleeces, and lower bodywear items such as skirts and trousers and whole body protective coveralls.

Insulation and ventilation are important functions at this mid-level and are most often achieved through trapping and releasing air respectively. For thermal stability, pockets of still air need to be kept within the system long enough for the air to be warmed from the heat generated by the body. However, this will cause an increase in internal humidity and lead to the saturation of the underlying layers unless the system's air is renewed frequently or the moisture is drawn out of the system (Sari and Berger, 2000). Structurally, air can be trapped or released most easily round the neck, wrists and waist areas through the use of a convertible collar that can be worn open or closed, a blouson style top or draw string trousers, and by using long sleeves with elasticated or turn back cuffs. Insulation properties can be engineered into the clothing system through use of both textiles and structural design. In fabrics, air pockets are created through constructions such as foam, cellular knits, or weaves, napping, pile, double woven or knitted structures, or batts of loose fibre wadding quilted together between two layers of fabric.

In addition to the management of heat and moisture generated from the body, the middle layer in the system can also carry additional protective properties such as ballistic protection, which is introduced into the system through specialist textile technology. Often protective functionality is achieved through rigid plate technology almost welded into the garment system and the textiles used lack flexibility both structurally and aesthetically. This is the point where protective functionality collides with design aesthetic. The textile system providing the function can dictate the overall shape and look of a garment, as rigid protective systems tend to be stiff and bulky which limits aesthetic design possibilities; in addition, surface manipulation processes such as printing and embroidery can damage the functionality. Waterproof/breathable membranes lose their water resistance when stitched, although this can be remedied by taping the seams, but breathability can be compromised by printing pastes or repellent finishes.

In the Metropolitan Police, body armour is an aesthetic issue for women. To accommodate the contours of the female, shaped ceramic body armour panels are used, which are technically very difficult to construct, in order to pass all the required tests; shaped panels which were intended to increase comfort and reduce weight on the breasts, were rejected by some women because of image. 'The "Madonna look" was ridiculed and women felt their authority was undermined' (authors' interview R von Szaley).

The innovative concept behind the Arctic Heat vest (also a collaboration with Sportwool®) is the encapsulation into a body protector of hydrophilic crystals which form a gel when immersed in water and can maintain the core body temperature, either hot or cold, for a considerable time. This vest can be worn directly over a garment and provide instant relief from heat stress but is a rigid and solid structure that limits the design possibilities. The aesthetic aspects have hardly been developed in the highly functional but unsympathetic styling. Another system that dictates the look of the garment is Airvantage by Gore and Associates which consist of inflatable tubes inside the vest. The technology provides adaptive insulation but is stiff and does not leave much scope for design. Further innovative design solutions are still needed in these areas.

External layer

The external layer is the final stratum; garments in this layer cover areas of the mid-level clothing and can also have direct contact with the skin at the extremities, usually at the hands, neck or on the head. This is perhaps the most complex of layers as it meets multiple requirements. It may need to be wicking, insulating, provide ease of movement, be wind and water proof and carry most of the protective functions that shield the user from the hazards of their particular external environment, in addition to aesthetic aspects. Garments in this group can be coats, jackets, heavy fleeces, whole body coverings, footwear, hats and gloves and can employ woven, knitted, non-woven and composite fabric structures.

One of the core requirements this layer must achieve is the management of heat and humidity generated by the body. Heat loss can be controlled structurally by the use of zippers and openings at strategic places, i.e., sleeves, back of neck, irrespective of the degree of moisture permeability particular to the material used in the external layer (Ruckman and Murray, 1999). However, this particular method requires the user to manage the renewal of air manually. This may not always be practical as the wearer's professional practice may require his full attention, such as in the situation of a firefighter. Any distraction could prove lethal.

Breathable membranes, for example Gore-Tex®, are introduced to the external strata through laminating methods that bond the membrane to one or more surfaces of a textile. This makes the garment resistant to drops of water from the external environment but permeable to moisture vapour generated from the body. Evidently, the individual properties of a textile can be lost within a system, and the success of the clothing system depends on the relationship between the different components. Therefore, if one of the items has low permeability to water vapour, for instance, the wicking performance of the entire system deteriorates. In addition, attention must be paid to co-ordination of different layers of the system. If both an outer and a mid-layer garment have impermeable membranes, then their effectiveness may be cancelled out. The procurement procedures for protective clothing must therefore also be co-ordinated. A designer should be sure to consider the wider context even if only commissioned to design certain elements of a clothing system. (See also Chapter 10 by Rossi.)

3.4 Reconciling fashion and function

3.4.1 Marketing and evaluation

Where the design of new products is carried out as part of a major research and development project, testing and evaluation naturally forms part of the standard procedures built into the development process outlined in section 3.2 above. However, trials are necessarily limited and often take place in fairly unrealistic laboratory circumstances. There is no substitute for wearer trials carried out over a period of time by the real users of the clothing systems, where feasible. The product development process therefore never concludes, but continues in response to user feedback, with adaptations being made to the products whenever possible as renewal and replacement occurs. The development of highly sophisticated responsive manikins for use in thermal comfort, fire, pressure, and crash testing has provided enhanced data in areas which are difficult to test safely with humans, e.g., military, fire and space applications (SATRA, 2003). (See also Chapter 9 by McCullough.)

Many claims are made by clothing manufacturers in promotional material concerning the performance and longevity of their products, especially in sports clothing which is not governed by CE marking regulations, and which are endorsed by well-known personalities. In the early development of sportswear and outdoor wear some of the prominent sportsmen and women within the activities themselves became consultants in the research and development process and helped to refine existing designs and develop new products for protective and performance clothing. These have developed into some of the most successful sportswear and outdoor brands such as Helly Hansen® and O'Neill®.

Branding and marketing is increasingly important to convey the technical message of invisible performance factors inherent in modern clothing. Wool fibre has recently undergone such a re-branding to attempt to rid itself of its persistent but somewhat anachronistic image of the past, and to position its natural properties and structural complexity within a technical and performance framework as 'nature's first smart fibre'. This was branded Woolscience in 2003, in order to appeal to a more masculine and younger user, reposition wool against its synthetic competitors, and to reverse the recent decline in its market share. Included in these recent developments are Deolaine®, a bacterial inhibitor for odours, and Arcana®, a descaled wool aimed to give a softer feel, similar to cashmere. The dual message is performance and comfort engendering wellbeing.

3.4.2 Case studies

Police

Within different contexts, such as the police, the protective aspect of clothing has to be balanced with its dual function as a recognisable uniform, serving as a form of corporate identity for the public. Following complaints from officers about the performance of their clothing, police forces across Scotland have recently collaborated to redesign their uniforms which have ranged from the formality of the original tunic first developed in the late 19th century, to casual clothing such as anoraks, 'old-fashioned woven jerkins' and sweaters. According to one reporter 'The new look finally sweeps away the impractical and old-fashioned tunic and replaces it with clothing that suits the realities of modern-day policing' (Qureshi, 2004). The fabrics were chosen from those developed for outdoor sports and aimed at preventing an officer from sweating profusely under the increasing burden of equipment, now weighing several kilograms. The design solution for the clothing system now has a more military ambience, and is currently being trialled. It includes a high visibility/reflective jacket, waistcoat comprising a polyurethane coated nylon material designed to protect officers from blood-borne viruses which may be transmitted at accidents or during violent incidents, and a shirt made from fabric which wicks away moisture. To aid ventilation, officers will be allowed to remove ties, although other forces have abandoned the shirt and tie in favour of t-shirts. There is also a lightweight fleece jacket which can be zipped into a waterproof outer jacket and 'cargo' trousers with multiple pockets (Qureshi, 2004). With the increasing impact of equal opportunities legislation, more consideration is now being given to the female form and fit, (so-called 'lady fit') in both military and civilian uniforms. In this case, the newly designed lighter weight body armour will be available in 'sculpted' form for female officers. However, carrying bulky equipment in trouser pockets is not a flattering female look, and could meet resistance for aesthetic reasons (see also Chapter 23 by Fenne).

Firefighters

In a similar manner to the Scottish police mentioned above, the diverse clothing practices of the fire services across the UK are being investigated within the

Integrated Clothing Project which has a remit to look at garment performance and make improvements to personal protective equipment and clothing by 2007. It is to be noted that there is no specific design input planned into this project, which will be tendered directly to manufacturers. The Manchester Fire Brigade currently uses a typical fire tunic comprising three strata of fabric: an outer shell made of Nomex® aramid fibre for flame resistance, with a fluorocarbon finish which gives an 80% fluid run-off and chemical protection; inside the shell a Gore-tex® membrane for sweat management, which allows moisture from the inside out, but is waterproof; an insulating layer of synthetic wadding by Duflot; and finally an inner lining of fire-retardant rayon. A cotton t-shirt is typically worn under the tunic with cotton/polyester trousers. (See Fig. 3.4.)

In the development of new base layer garments outlined in section 3.3.2, inspiration was taken from ski-wear, the most fashion-conscious of the active sports, to move to polyester fabrics. Whilst Coolmax® polyester t-shirts were popular and comfortable, they did not perform well in burn tests, and the Sportwool® solution identified had the best performance for the available budget. In addition, the durability of the new garment was three times that of a cotton t-shirt which balanced out the increased costs. Styling changes were made from inset sleeve to raglan sleeve and the use of a scooped back in order to emulate the fit of sports garments, and create a more inclusive fit for women. Certain clothing introduced for climatic protection such as anoraks had not been taken up by the firefighters, as they were deemed unfashionable, but crossovers from sportswear including the use of brand names such as Polartec® fabric encouraged a new outer garment to be accepted and worn. A similar effect was observed when safety goggles which were both unattractive and uncomfortable were replaced by more fashionable ski-type goggles with added features such as anti-misting.

One brigade recently completely redesigned their fire-fighting clothing, and developed a system which, contrary to the traditional loose and long fire tunic, comprised salopette style trousers and a short blouson jacket in a silhouette and fit that was much closer to the body. However, the change in the amount of air trapped within the clothing system caused in some cases much greater heat stress, resulting in an unacceptable increase of 2.5 °C in core body temperature (authors' interview K Whitehead, Greater Manchester Fire Service). Whether fashion or corporate identity played a significant part in any of these decisions remains unknown, however it appears that the design and product development process broke down in certain areas such as preliminary research and user testing.

Safety clothing and accessories

Personal safety is a functional prerequisite and preventive aspect of protective clothing which can be designed into garment systems, most obviously through the use of colour, especially fluorescent colours and retro-reflective strips for high visibility when working in hazardous environments (railway workers, road workers, mountain climbers, etc.). However, ironically, the ubiquitous nature of fluorescent clothing and trimmings, and its use in consumer goods, has now begun to reduce its effectiveness in visibility in some urban contexts, in so far as work-based clothing is often used as a criminal disguise, and drivers tend not to notice cyclists and motorcyclists, as accident statistics have recently shown (Ronson, 2005). These ‘invisible’ fluorescents indicate that there is a need for constant vigilance, updating and reinvention, and how attention must be paid to wider cultural aspects in the context of design.

Accessories (bags, hats, gloves, etc.) and footwear have gained in importance in commercial fashion over the last decades as a vital part of daily apparel, as is evident in the market for sports and non-sports trainers. They offer many opportunities for both functional and innovative solutions particularly to the exigencies of the urban working environment, where an increase in use of portable electronic items is most marked, together with a perceived increase in thefts. Designers and urban style leaders Vexed Generation are credited as the originators of the one-shouldered bag with integrated front pocket for a mobile phone, an accessory which left hands free for cycling for example, but allowed for instant communication (Bolton, 2002: 44). Some highly functional protective items become design classics (for example, the Dr Martens boots or Levi 501 jeans) and as such do not change radically with fashion. Footwear designer Nick O’Rorke cites comfort and performance as the key factors in his Tsubo range (named from the Japanese for pressure point). Taking the protective aspects of rock-climbing shoes into fashion, they incorporate an air bubble outsole for cushioning, with a double-density polyurethane moulded midsole that allows air flow, and also have an antibacterial sock liner. (‘Tsubo charged’ *Footwear News* 23.8.04.)

Protective clothing has recently begun to merge with fashion clothing in what Bolton (2002) articulates as the ‘supermodern wardrobe’, garments specifically designed for mobility and protection in urban environments by leading designers, using high-technology technical fabrics and integrating many functionalities. Bolton states ‘Often, the metropolitan experience is characterised by insecurity and paranoia. Indeed, the contemporary urban landscape is shaped by our preoccupation with fear.’ An initiative set up in 2000 by Dr Lorraine Gamman named ‘Design against Crime’ has taken personal protection into the design education arena, and aims to promote design as a tool for crime prevention and personal safety, particularly in the realm of clothing and accessories. Supported, amongst others, by the Home Office and the Design Council, the philosophy is to anticipate likely crime opportunities and correct them in advance rather than apply ‘retro-fit’ solutions to existing products. Accordingly, a range of prototypes was developed, in co-operation with military and emergency service bag specialists H Fine and Co, of designs for handbags and computer bags, both high risk for theft and mugging. Some concepts were commercialised in the Karrysafe® range by Vexed Generation, which included the 'Screamer' laptop bag which triggers a 138 decibel alarm if snatched, and the Bodysafe® fabric belt worn under jeans for personal credit cards, etc. (Gamman and Hughes 2003; www.karrysafe.com.)

3.5 Future trends

This is an exciting phase of experimental research and development within the textile industry, as the universality of textiles within our most immediate and intimate surroundings (the 'portable environment' posited by Watkins (1984)) and in our daily working and living spaces (interior textiles) provides a perfect interface for integrated and enhanced functionality. Several products are beginning to enter the most avant-garde areas of the fashion industry, which are traditionally the first to experiment with radical new ideas whether derived from new technologies or conceptual frameworks. The continued development of textiles with integrated electronics, phase changing or other physical properties, which respond to external environmental changes or internal body conditions, will eventually lead to more effective functional clothing for protection. Some technologies are at an advanced stage of research with existing prototypes, others are still very much at the concept stage. The impact of nanotechnology can already be found in coatings for textiles which allow stain and liquid repellency (marketed rather confusingly as self-cleaning) and the use of nanoparticles of silver in yarns to create anti-bacterial woven or knitted fabrics, currently being used in socks (e.g. SoleFresh®) and other applications.

Much research and development is being focused on the concept of clothes which morph and change to suit the user's individual needs. Shape memory polymers have begun to be utilised for cloth, and Italian manufacturers Corpe Nova's R&D unit Grado Zero Espace have created a prototype metallic polymer shirt whose sleeves they claim will shorten with heat from the sun, and lengthen again on cooling. The same shirt, it is claimed, can be 'ironed' by directing warm air over the crumpled surface whilst being worn (Battrick, 2003).

Over the past ten years, there has been widespread interest and research into the concept of 'wearable computers'. The first wave of research produced clothing prototypes with integrated computers wired into garments, and distributed the functions of the computer –processor, keyboard and monitor – into different parts of the clothing or accessories. Portable electronic devices for communication, location and entertainment have also been incorporated. A limited number of commercial applications resulted, such as the 2001 Cagoon jacket produced as a collaboration between Levi's and Philips, but they often experienced difficulties with aesthetics, bulky power sources, washing or cleaning procedures and with the fact that the requirements of the user will change constantly with fashion and lifestyle. Dent (2004) put it succinctly: 'Consider the Mithril® shirt: is this really a "portable computer" or simply the hardware of a computer strapped to a vest. If these devices are to become wearable, they must become a seamless and unobtrusive part of the clothing.' However, the 'mp3blue' jacket by Rosner and Infineon Technology, launched onto the market in 2004, incorporated removable or encapsulated electronic components designed to withstand washing. Softswitch and Eleksen pioneered soft keyboards and interfaces using different technologies, and further commercial products are in preparation.

The next generation of research has focused on the embedding of electrical functions directly into textiles using conductive polymer yarns or metal coated yarns introduced into woven or knitted structures, and using soft textiles sensors and actuators to provide functionality and monitoring. Medical research is now a key driver for functional integration for remote monitoring of patients and for wellbeing during sports or remote and hazardous activities (for example, Wealthy, Eleksen, De-tect). Further developments have seen conductive circuits printed onto textiles, and the incorporation of optical fibres and photonics into woven structures, which have the potential to change colour or act as a flexible display (see also Chapter 7). The key factor still to be resolved is the robustness of the systems, before ubiquitous applications can be developed. When this transpires, there will be a significant impact on both protective and everyday clothing.

A further factor which will have a major impact on the industry is the paradigm shift from mass production to mass customisation and personalisation, particularly relevant wherever military and civilian uniforms have to be adjusted for individuals. Three-dimensional body scanning and visualisation technologies provide an opportunity and the means for customised design and fitting of many types of apparel – shoes, jeans, suits, shirts, etc. Examples can be seen in both American and European retail and web-based environments, such as Brooks Brothers of New York, Odemark in Germany, and the customised 'virtual try-on' system for jeans established in 2002 by Bodymetrics at Selfridges in London.

These developments, together with continued research into new materials and manufacturing processes, and technology transfer are being applied to a number of processes such as knitting, weaving and rapid prototyping technologies for the production of clothing and accessories, which will integrate fashion design, materials science and micro computing. One project undertaken by footwear company Prior2Lever, in conjunction with researchers at London College of Fashion, is enhancing the performance and comfort of football boots, by creating a customised pair of boots on demand from an individual foot scan, which also combines a customised sole directly manufactured from powdered polymer material, using stereolithography to produce an individual 3D form to exactly fit the footballer's feet, improving fit and reducing injury.

One of the key drivers for new advances in technology for textiles and clothing comes from the military sector, which seeks to equip troops with the highest specification personal protective equipment, and therefore sponsor specific research programmes. The US military has recently embarked on the Rapid Fielding Initiative, the 'largest single project to properly protect and outfit the modern soldier', sourcing mainly from America. The majority of the technology that appears in the final product will be introduced at the fibre and textile level, which is increasingly where real innovation lies. Future operational equipment and clothing are envisaged to be lightweight multifunctional garments that integrate:

> intelligent textiles serving as the backbone for warfighters' electronics, optics and sensor suites
> lightweight ballistic protection
> improved camouflage and signature management
> self-deactivating chemical/biological protective membrane
> antimicrobial protection
> improved environmental protection
> reduced weight and bulk with improved fit, comfort and durability.
> (Kinney, 2004)

Other NATO Nations including the UK, France, Holland, Denmark, and Germany also have research and development programmes with similar objectives. This menu of functionalities may eventually be incorporated into multi-layered textile structures with external camouflage layer, internal membranes and embedded sensors, data and power systems. Enabling technologies are nano- and microtechnology, electro-textiles, flame-retardant chemistry in fibres and finishes, and composite structures, but power sources, textile materials and weight continue to be barriers to achieving the goal. Total integration may be achieved only when multiple protective capabilities can be enabled in a single textile without increasing weight, bulk and heat stress. This type of military research push certainly points the way for further integration of functionalities at the textile level in future civilian protective clothing, and so eventually to both functional and fashionable everyday wear.

Clothing is the interface between the wearer and their environment, within which will be embedded an increasing range of functionalities, within the materials and textiles structures and in the design and realisation of the garments, working to complement each other. Research already under way will result in direct customised manufacturing using both traditional and novel methods, and technologies will emerge which allow clothing to be made in entirely new ways. There will continue to be higher demands and expectations of functionality and performance from clothing, and clothing systems for protection will move towards lighter weight but effective solutions. Multi-functionality and versatility in fibre and textile systems will mean a reduction in the number of individual layers of clothing required. All the indications are that current research will deliver, in the relatively near future, garments and clothing systems which will be more protective, but also more adaptable in a multitude of ways: sensory, emotive, responsive, receptive, transmissive, regenerative, and aesthetic. In the meantime, fashion is playing an increasingly important role in achieving positive acceptance of personal protective clothing in today's design-conscious environment.

3.6 Sources of further information

Standards

See British Standards Institute websites www.bsonline.techindex.co.uk and www.bsi-global.com
American Society for the Testing of Materials (ASTM)

Journals

Clothing and Textiles Research Journal, International Textile and Apparel Association
The Journal of Clothing Technology and Management
International Journal of clothing science and technology
Company Clothing

Website

www.director-e.com Corporate Clothing Directory

Organisations

The Textile Institute
British Textile Technology Group www.bttg.co.uk
SATRA Technology Centre www.satra.co.uk

3.7 References

Adams SA, Slocum AC, Keyserling WM (1994) A model for protective clothing effects on performance. *International Journal of Clothing Science and Technology*, Vol. 6, No. 4, p. 6, MCB University Press.

Battrick B (ed.) (2003) *A thread from space to your body*, ESA Technology Transfer Programme, Noordwijk, ESA Publications.

Bolton A (2002) *The Supermodern Wardrobe,* London, V&A Publications.

Brownless NJ, Anand SC, Holmes DA, Rowe T, Silva AD (1995) 'The quest for thermo physiological comfort', *The Journal of Clothing Technology and Management*, Vol. 12, No. 2, pp. 13–23

Carr H and Pomeroy J (1992) *Fashion design and product development*, Oxford, Blackwell.

Dent A (2004) 'Wearables', *www.toy-tia.org/access/development/d-articlearchive12.html* (accessed 1.7.04).

Ellis A, Brook D (2004) 'Moisture Management Base Layer Project', paper presented at Survival 2004 Conference in Leeds, UK (Sept).

Entwistle J (2000) *The Fashioned Body*, Cambridge, Polity Press.

Entwistle J (2001) 'The Dressed Body', in Entwistle J and Wilson E, *Body Dressing*, Oxford, Berg.

Gamman L, Hughes B (2003) 'Thinking Thief' *Ingenia*, London, RSA Publications.

Joseph N (1986) *Uniforms and Nonuniforms: Communication through Clothing* Contributions in Sociology no 61, New York, Greenwood Press.

Kinney RF (2004) 'Future DOD directions and its impact on textiles', Techtextil Symposium North America (May).

Lamb JM, Kallal M J (1992) 'A conceptual framework for apparel design', *Clothing and Textiles Research Journal*, Vol. 10, No. 2, pp. 42–47.

Maslow A H (1954, 1970) *Motivation and Personality*, London, Harper Row.

McCann J (1999) Establishing the requirements for the design development of performance sportswear. Unpublished MPhil thesis, University of Derby.

Perkins HM, Crown EM, Rigakis KB, Eggerttson BS (1992) 'Attitudes and behavioural intentions of agricultural workers toward disposable protective coveralls', *Clothing and Textile Research Journal*, Vol. 11, No. 1, Fall.

Pitimaneeyakul U, LaBat KL, DeLong MR (2004) 'Knitwear product development process: a case study', *Clothing and Textile Research Journal*, Vol. 22, No. 3, pp. 113–121.

Qureshi Y (2004) 'The new black for the thin blue line', *Scotland on Sunday* 18.04.04.

Raheel M (ed.) (1994) *Protective clothing systems and materials*. New York, Marcel Dekker.

Renbourn ET (1971) *The psychology of clothing with materials in mind*, Third Shirley International Seminar 'Textiles for comfort' New Century Hall, Manchester.

Ronson J (2005) 'Now you see them ', *The Guardian Weekend* supplement 15.01, pp. 14–19.

Ruckman JE, Murray R (1999) 'Engineering of clothing systems for improved thermophysiological comfort', *International Journal of Clothing Science and Technology*, Vol. 11, No. 1, pp. 37–52, MBC University Press.

Sari H, Berger X (2000) 'A new dynamic clothing model. Part 2: Parameters of the underclothing microclimate', *International Journal of Thermal Science*, Vol. 39, pp. 646–654, Elsevier.

SATRA Spotlight (2003) *Manikin testing* (protective clothing; test methods; burns) p. 15.

Smith EJ (1993) 'The comfort of clothing', *Textiles,* Issue No. 1, pp. 18–22.

Sweetman P (2001) 'Shop-Window Dummies? Fashion, the Body, and Emergent Socialities', in Entwistle J and Wilson E, *Body Dressing*, Oxford, Berg.

Watkins SM (1995, 1984) *Clothing the portable environment,* Iowa, Iowa State University Press.

Thermal (heat and fire) protection

A R HORROCKS, University of Bolton, UK

15.1 Introduction

That textiles on the one hand protect us from external agencies in our daily lives and yet pose a significant fire hazard may appear as a paradox to the average consumer, especially if, for example, he or she is to consider the requirements of a protective garment for an industrial worker in a hazardous environment or a firefighter. However, as demands for higher levels of protection for wearers in hazardous environments (usually associated with occupational and professional requirements) increase, the textile and apparel industries continue to overcome design and constructional challenges that offer the right levels of protection for defined external agencies that operate individually or in concert. In addition, having engineered into a textile the desired level, the product must still function as a textile in terms of its aesthetic, comfort, durability and aftercare expectations.

Given that protective textiles often have to protect against more than one agency and that technologies available may not only operate against each other and compromise aesthetics and comfort, the final solution is often a balance. In the case of heat and fire protection, addressing these hazards is the principal goal and other properties, such as breathability and comfort, may be less well satisfied. In fact, in the case of firefighters' garments, for example, the outer fire protective garment assembly, because of its weight and lack of moisture permeability, easily gives rise to heat stress or shock to wearers in typical fire surroundings. Therefore, conditions may have to applied to their use such as definition of maximum wearing times in real fire scenarios. In the case of barrier textiles designed to protect underlying and inanimate, but potentially flammable materials such as upholstery interior fillings, this is obviously not a problem. However, in commercial aircraft seating where fire protection levels have to be high, so also does comfort since passengers may be in contact with seating for up to 12 hours at a time; far more than is usually the case in a domestic environment.

In this chapter, major focus will obviously be on fire and heat protection and the means of conferring these features into textile products and assemblies and so other factors, such as comfort, ballistic resistance, chemical and biological agency resistance will only be commented on if particularly relevant to a particular thermal protective solution or system. Other chapters in this book consider related and often interacting issues such as multifunctional treatments (Chapter 8), comfort (Chapter 10) and biological and chemical (Chapters 12, 16 and 20) and ballistic (Chapter 19) resistance.

This chapter will concentrate on factors that assist us in understanding the nature of the thermal hazards as they apply to textiles and the means of addressing them. The latter will examine the available strategies at fibre, yarn, fabric, chemical finishing and textile assembly levels for introducing defined levels of thermal protection. Finally, the related testing and performance assessment methodologies that enable the quantification of defined levels and qualities of protection are discussed. Typical examples of thermally protective textiles include the following:

- protective clothing for workwear, hazardous industrial occupations, firefighters and defence personnel
- outer furnishing fabrics that protect underlying fillings in domestic, contract and transport applications
- barrier textiles that may prevent fire spread (e.g., fire curtains) or protect underlying surfaces from heat and fire spread
- extreme hazard protection, e.g., furnace operators' aprons to protect against hot metal splash, fire entry suits, racing car drivers' suits.

While there is a considerable literature in this area and this chapter is not meant to be a comprehensive literature review, a recent selection of relevant publications are those by Barker and Coletta (1986), Mansdorf *et al.* (1988), Raheel (1994), Johnson and Mansdorf (1996), Stull and Schwope (1997), Scott (2000), Bajaj (2000), Horrocks (2001) and Hearle (2001).

15.2 Fire science factors

Thermal protection relates to the ability of textiles to resist conductive, convective, radiant thermal energy or a combination of two or more. For example, a flame constitutes a convective oxidative chemical reaction zone in which the energy is contained within the extremely hot gas molecules and particulates, including smoke. Typical textile flame temperatures may range from about 600 to 1,000 °C (see Table 15.1) and when a flame impinges upon a textile surface, not only is it subjected to the high temperature of the flame but also the chemical intermediates of the reaction zone, which may increase the likelihood of its degradation and ignition. Thus the selection of textile outer fabrics for a firefighter's tunic or an industrial worker's coverall should take account of both the temperature and reactivity of an impinging flame source.

Radiant thermal energy, however, is electromagnetic radiation emitted by a hot surface or a flame and this infra-red is absorbed by the molecular structure of

Table 15.1 Thermal transitions and flame temperatures of the common fibres

Fibre	T_g, °C (softens)	T_m, °C (melts)	T_p, °C (pyrolysis)	T_c, °C (ignition)	T_f, °C*	LOI, %
Wool	—	—	245	570–600	680, 825 (v)	25
Cotton	—	—	350	350	974 (h)	18.4
Viscose	—	—	350	420	—	18.9
Nylon 6	50	215	431	450	—	20–21.5
Nylon 6.6	50	265	403	530	861 (h)	20–21.5
Polyester	80–90	255	420–447	480	649 (h), 820 (v)	20–21
Acrylic	100	>220	290 (with decomp)	>250	910 (h), 1050 (v)	18.2
Polypropylene	−20	165	470	550	—	18.6
Modacrylic	<80	>240	273	690	—	29–30
PVC	<80	>180	>180	450	—	37–39
Meta-aramid (e.g. Nomex)	275	375–430 (decomp)	425	>500	—	29–30
Para-aramid (e.g. Kevlar)	340	560 (decomp)	>590	>500	—	29

Note: * flame temperatures recorded only for fibres that burn in air; h is for horizontal and v is for vertically downward burning fabrics (Rebenfeld *et al.*, 1979).

the surface fibres and any coatings present, raising the temperature to several hundred degrees Celsius, which if high enough (typically >300 °C) promotes thermal degradation (or pyrolysis) and even ignition. In a real fire, it is usually the radiant heat that causes it to spread rapidly by heating up and igniting materials some distance away from the fire. Again, it is obvious that protective clothing should resist the effects of heat radiation if it is to be effective.

Finally, conductive heat is that which flows from a hotter surface to a cooler one, which if a textile may promote thermal degradation and ignition. Protective clothing for furnace personnel who risk contact with molten metal splashes must resist such threats. However, in many thermally hazardous environments, a combination of conduction, convection and radiation may be operating in concert, and usually the last two are associated with flame sources in particular.

15.2.1 Criteria that define heat and/or fire performance

Once heat is absorbed by a textile fibre, it may promote physical or chemical change or both. All organic fibre-forming polymers will eventually thermally degrade at or above a threshold temperature often defined as the pyrolysis temperature, T_p. This may be influenced by the presence of oxygen in the air and so T_p may vary whether the fibre is heated in nitrogen, air or vitiated air (often present in a typical fire). Typical values of T_p are listed in Table 15.1 for the more common fibres. Once heated above this temperature in air, ignition at a higher temperature, T_i, usually follows and these are also listed in Table 15.1. However, flame temperatures are usually higher still, and where available, are included for those fibres that burn in air.

While the above temperatures are associated with chemical change, some fibres undergo physical change as an initial softening followed by melting in some cases. The former is defined as a second-order temperature, T_g, and the latter as a melting temperature, T_m. Table 15.1 lists these, which for the so-called thermoplastic fibres, are less than T_p and T_i. For the conventional textile fibres like polypropylene, polyester and nylons (or polyamides) 6 and 6.6, the relatively low temperatures at which these physical transitions occur mean that textiles comprising them offer little of no protection against thermal energy. Not only will they shrink and deform when heated, but also complete melting and disintegration of any previous textile structure will occur with dire consequences for the wearer or underlying surface.

15.2.2 Levels of thermal resistance

Based on the above discussion, it is evident that different thermal threats will promote a number of often interrelated physical and chemical changes in an exposed textile substrate including any finishes or coatings that are present. While there is no accepted hierarchy of threat and hence levels of resistance and thermal protection required, some performance and standard test methods do recognise this. For example, BS5852:1979 Parts 1 and 2 and its variants since 1979 (see section 15.5) tests the ability of upholstered furnishing fabric internal filling composites to resist ignition and of the outer cover to protect the inner components. The related standard BS7176:1991 advises how the test may be used to assess ignition hazards relating to various application environments of differing hazard level (see section 15.5). This has led, of course, to a whole family of textile solutions that have different levels of thermal and fire protection.

Levels of thermal resistance may be simply defined with respect to maximum temperature of exposure criteria, although time of exposure is a significant parameter as well. For thermal environments where flame or spark sources of ignition are absent (e.g. hot surfaces, radiant energy, molten metal splash), temperatures may be significantly less than flame temperatures and so even thermoplastic fibres can resist some thermal hazards for significant periods of time. Once temperatures rise significantly above respective T_g values and approach melting temperatures, then most textiles comprising these fibres lose any protective value. In fact, they can prove to be a hazard through shrinkage onto underlying surfaces thereby removing any thermally insulating air layers. Fabrics designed for defence purposes often require only non-thermoplastic fibres to be present, especially for inner clothing items, and so remove the possibility of this often-termed ‘shrink wrapping’ effect (Scott, 2000). Since most conventional synthetic fibres undergo physical transitions no greater than about 265 °C (in the case of nylon 6.6 and polyester), temperatures of about 200 °C are seen as a maximum for their safe use, if the relatively more sensitive polyolefin fibres are ignored (see Table 15.1).

For thermal threats yielding temperatures above 200 °C, essentially non-thermoplastic fibres only should be used and we should differentiate between those fibres that are flame retardant and those that are heat resistant – the two are not necessarily related! The former will yield textiles that resist defined ignition sources and if they do ignite when the source is present, have reduced burning rates and times once the source has been removed. Ideally, if textiles comprising this type of fibre are to continue to offer thermal protection, the heated fibres should convert to char and so the textile now provides a carbonaceous char replica of itself that is extremely flame resistant (Horrocks, 1996). Most flame retardant fibres start to become effective above about 250 °C when component fibres start to thermally degrade (see Table 15.1) and the flame retardants present start to interact either independently or in concert with respective fibre chemistries (Horrocks and Price, 2001).

Heat resistant fibres, however, are those having chemical structures that are little changed by temperatures well above the 300 °C level and, in the case of

Table 15.2 Maximum service lifetimes for heat resistant fibres in thermally protective textiles (Horrocks *et al.*, 2001)

Fibre genus	Second-order temperature, °C	Melting temperature, °C	Onset of decom-position, °C	Maximum, continuous use temperature, °C	LOI, %
Melamine-formaldehyde	NA	NA	370	190	32
Novoloid	NA	NA	>150	150/air; 250/inert	30–34
m-Aramid	275	375–430 (decomp)	425	150–200	28–31
p-Aramid	340	560 (decomp)	>590	180–300	29–31
Arimid (P84)	315	—	450	260	36–38
Aramid-arimid	<315	—	380	NA	32
Semicarbon	NA	NA	NA	~200/air	55
PBI	>400	>NA	450/air; 1000/inert	~300 (est)	>41
PBO	—	—	650; >700/inert	200–250(est)	68

Notes: NA = not applicable; (decomp) = with decomposition; (est) = value estimated from data in cited references.

ceramic fibres, above 1,000 ºC. For textiles used in high-temperature industrial processes, such as gas and liquid filtration, long-term exposures to temperatures of about 100 ºC are often required, but not all these fibres are used in thermally protective applications (Horrocks *et al.*, 2001). However, in long-term exposure, thermally protective applications, we need to be able to define maximum service life temperatures and these are listed in Table 15.2 for selected heat resistant fibres (Horrocks *et al.*, 2001).

Heat resistant fibres are more often than not also flame resistant because they have chemical structures resistant to thermal degradation in the first place (see Table 15.1) and may also form carbonaceous chars and few flammable, fuel-forming volatiles (Horrocks, 1996). Flame resistance may be conveniently measured as a limiting oxygen index value (Horrocks *et al.*, 1987), which for textiles with values greater than 21 (the percentage volume concentration of oxygen in air), indicates less vigorous burning than if less than 21. Fibres and textiles having LOI values >26–28 tend to be flame retardant in air and will pass simple vertical fabric strip tests (see section 15.5), while those having values in excess of 30 are highly flame retardant. LOI values are also included in Table 15.1.

15.3 Flame retardant fibres and textiles

For most thermal protective applications, textiles comprising 100% synthetic and hence thermoplastic fibres must be avoided for reasons already stated. The only time 100% synthetic textiles may be used is if either they are part of a composite structure in which, for example, they are present as a component with a flame retardant/heat resistant majority fibre construction or a char-forming, flame retardant back-coating is present. Examples here are the 100% medium weight (e.g. 200–300 gsm) polypropylene contract seating fabrics to which a flame retardant back-coating (e.g. an acrylic based, antimony-bromine-containing system (Horrocks, 2003)) has been applied, often at high levels (e.g. typically >50% w/w with respect to fabric). Typical blend examples that include thermoplastic fibres are:

- flame retardant cotton-rich (e.g. 55%) – polyester (e.g. 45%) blends for protective workwear
- flame retardant wool (e.g. 90%) – nylon 6.6 (e.g. 10%) blends for aircraft seating outer fabrics.

The major flame retardant fibres used in flame retardant, protective textiles are listed in Table 15.3.

Within this group, the flame retardant properties may be conferred by chemical treatment or finishing of conventional fibres, use of inherently flame retardant fibres, blending of flame retardant and non-flame retardant fibres or by the application of a surface coating. Some flame retardant finishes are non-

Table 15.3 The major flame retardant fibres including thermoplastic variants used in protective fibre blends

Fibre	Flame retardant structural components	Mode of introduction
Natural		
Cotton	Organophosphorus and nitrogen-containing monomeric or reactive species, e.g. Proban CC (Rhodia), Pyrovatex CP (Ciba), Aflammit P and KWB (Thor), Flacavon WP (Schill & Seilacher)	F
	Antimony-organo-halogen systems, e.g. Flacavon F12/97 (Schill & Seilacher), Myflam (Noveon)	F
Wool	Zirconium hexafluoride complexes, e.g. Zirpro (IWS); Pyrovatex CP (Ciba), Aflammit ZR (Thor)	F
Regenerated		
Viscose	Organophosphorus and nitrogen/sulphur-containing species, e.g. Sandoflam 5060 (Clariant, formerly Sandoz) in FR Viscose (Lenzing)	A
	Polysilicic acid and complexes, e.g. Visil AP (Sateri)	A
Inherent synthetic		
Polyester	Organophosphorus species: Phosphinic acidic comonomer, e.g. Trevira CS (Trevira GmbH, formerly Hoechst), Avora CS (KoSA); phosphinate diester comonomer, Heim (Toyobo, Japan); phosphorus-containing additive, Fidion FR (Montefibre), Brilén FR (Brilén, Spain)	C/A
Acrylic (modacrylic)	Halogenated comonomer (35–50% w/w) plus antimony compounds, e.g. Velicren (Montefibre); Kanecaron including Protex (Kaneka Corp.)	C
Polypropylene	Halo-organic compounds usually as brominated derivatives, e.g. Sandoflam 5072 (Clariant, formerly Sandoz);	A
	Bromo-phosphorus compound: FR-370/372 (Dead Sea Bromine Group)	A
	Hindered amine: NOR116 (Ciba)	A
Polyhalo-alkenes	Polyvinyl chloride, e.g. Clevyl (Rhovyl SA), Fibravyl (Rhone-Poulenc)	H
	Polyvinylidene chloride, e.g. Saran (Saran Corp.)	H

Key
F: chemical finish
A: additive introduced during fibre production
C: copolymeric modifications
H: homopolymer

durable to laundering, others may be semi-durable and withstand a single water soak or dry cleaning process and fully durable ones may withstand many domestic or commercial wash cycles, usually in excess of 50. Durability requirements are usually determined by the application and specified by regulation or the customer. Since the accumulation of oily soils on textiles during use often negates the effect of flame retardant properties present, laundering and aftercare requirements may also be closely defined by regulation or need. For example, protective workwear may require laundering after one day's wearing and protective textiles in defence applications require military personnel to be aware of the aftercare requirements if performance is to be maintained (Scott, 2000).

The most commonly used, flame retarded protective textiles for the workwear markets are those comprising flame retardant cellulose fibres. They also find application in military and emergency applications as well as furnishings. Flame retardant cellulosic protective textiles generally fall into three groups based on fibre genus, namely flame retardant cotton, flame retardant viscose (or regenerated cellulose) and blends of flame retardant cellulosic fibres with other fibres, usually synthetic or chemical fibres. They all have the advantage of being durable to most aftercare treatments, they are very cost-effective and, most importantly, when exposed to a flame or heat source, convert to a carbonaceous char and so continue to offer protection to underlying surfaces.

15.3.1 Flame retardant cottons

All flame retardant cottons are usually produced by chemically after-treating fabrics as a textile finishing process which, depending on chemical character and cost, yield flame retardant properties having varying degrees of durability to various laundering processes. For extreme durability chemically reactive, usually functional finishes are required to give durable flame retardancy (e.g. alkylphosphonamide derivatives (Pyrovatex, Ciba; Aflammit KWB, Thor; Flacavon WP, Schill & Seilacher; Pekoflam DPM (Clariant)); tetrakis (hydroxymethyl) phosphonium (THP) salt condensates (Proban, Rhodia; Aflammit P, Thor). Generally, however, phosphorus levels of 1.5 to 4% (w/w) on fabric are used which can give finish add-ons in the range of 5 to 20% (w/w) depending on the finishing agent phosphorus content. The actual level used depends on both the fabric weight (typically 200–350 gsm for protective end-uses) and the level of protection required.

Most of these treatments have become well-established during the last thirty to forty years and few changes have been made to the basic chemistries since that time. The earlier review by Horrocks (1986) and the more recent update (Horrocks, 2003) fully discuss the relevant chemistries and technologies. During this same period, many other flame retardants based on phosphorus chemistry, have ceased to have any commercial acceptability for reasons which include toxicological properties during application or during end-use, antagonistic interactions with other acceptable textile properties and cost (Horrocks, 1986). The examples cited above may be considered to have stood the test of time in terms of their being able to satisfy technical performance demands and enable flammability regulatory requirements to be met, while having acceptable costs and meeting health and safety and environmental demands. It is probably true to say, that durably flame retardant industrial workwear commands a significant proportion (probably >90%) of this market where a combination of FR performance, comfort, launderability and cost are the determining factors. This is not to say that FR cotton does not find application in more exotic end-uses, however – its use in the US Space Shuttle programme for protective apparel was reported 25 years ago (Dawn and Morton, 1979).

15.3.2 Flame retardant viscose

These usually have flame retardant additives incorporated into the spinning dopes during their manufacture, which therefore yield durability and reduced levels of environmental hazard with respect to the removal of the need for a chemical flame retardant finishing process (see Table 15.3). The thermal performance of these fibres is very similar to those of the flame retarded cotton fibre examples above. The polysilicic acid-containing Visil (Sateri, Finland) flame retardant viscose fibre is particularly interesting in that not only is it phosphorus-free but on heating, both a carbonaceous and siliceous char is formed (Horrocks, 1996). The presence of the silica in the residue, ensures that thermally exposed fabrics revert to a ceramic char, thus affording high levels of protection to temperatures as high as 1,000 °C.

15.3.3 Flame retarded cellulosic blends

In principle, flame retardant cellulosic fibres may be blended with any other fibre, whether synthetic or natural. In practice, limitations are dictated by a number of technical factors including compatibility of fibres during spinning, fabric formation and chemical finishing. Of particular relevance to fire performance is the last factor since flame retardant treatments must not adversely influence the characteristics of the other fibres present in the blend during their chemical application. Furthermore, additivity and, preferably synergy, should exist in the flame retardant blend. It is important to note, however, that with some flame retardant blends, antagonism can occur and the properties of the blend may be significantly worse than either of the components alone (Horrocks, 1986). Consequently, the current ‘rule of thumb’ for the simple flame retardant finishing of blends is to apply flame retardant only to the majority fibre present and enable this component to confer flame retardant behaviour on the minority components.

The prevalence of polyester-cotton blends coupled with the apparent flammability-enhancing interaction in which both components participate (the so-called scaffolding effect, reviewed elsewhere (Horrocks *et al.*, 1987; Horrocks, 1986)) has promoted greater attention than any other blend. However, because of the observed interaction, only halogen-containing coatings and back-coatings find commercial application to blends which span the whole blend composition range (see below). Most durable finishes for protective cellulosic textiles function best on cellulosic-rich blends with polyester where the char-forming majority component not only supports and extinguishes the minor polyester present, but also prevents hole formation and disintegration of the exposed fabric. Thus, phosphorus-containing cellulose flame-retardants, such as the THP-based systems like Proban CC (Rhodia) on blends containing no less than 55% cotton offer a combination of flame retardation and acceptable handle and comfort, unlike polyester-rich blends. The THP condensate is substantive only on the cellulose content and so requires over 5% (w/w) phosphorus to be present on this component in order to confer acceptable flame retardancy to the whole blend. In order to achieve the high finish levels necessary, often a double pass pad (or foam)-dry stage is required before the THP-condensate-impregnated fabric is ammonia-cured in the normal way. However, high phosphorus and hence finish levels may lead to excessive surface deposits on fibres which often reduce durability to laundering and create unacceptable harshness of handle. Because such an application only works well on medium to heavy weight fabrics (> 200 gsm), they are particularly effective for protective clothing applications. The use of a cotton-rich blend here is also advantageous because the lower polyester content confers a generally lower thermoplastic character to the fabric with less tendency to produce an adhesive molten surface layer when exposed to a flame.

Less used in protective workwear, but often preferred in furnishings because of superior dyestuff and print compatibility, are the methylolated phosphonamide finishes (e.g. Pyrovatex CP, Ciba), but these are effective only on blends containing 70% or less cellulose content. This is because the phosphorus present is less effective on the polyester component than in THP-based finishes (Horrocks, 1986). The reasons for this are not clear but are thought to be associated with some vapour-phase activity of phosphorus in the latter finish on the polyester component.

If a blend component does have vapour phase activity then this may be transferred to the cellulosic component. This certainly is the case in blends of cotton and PVC and, more recently, with modacrylic fibres. The Protex M range of fabrics feature blends of the modacrylic Kanecaron Protex fibre (see Table 15.3) with cotton in almost equivalent fractions as a 55% modacylic/45% cotton composition. The fabrics are suitable for furnishings, bedding, protective clothing including welding and similar hazard protection.

15.3.4 Flame retarded wool and blends

Within the area of flammability of all so-called conventional fibres, wool has the highest inherent non-flammability and so is particularly attractive for protective textile end-uses such as uniforms, coveralls, transport seatings and domestic and contract furnishings, where heavier fabrics may be used and the aesthetic character of wool may be marketed. Table 15.1 above shows it to have a relatively high LOI value of about 25 and a low flame temperature of about 680 °C.

Once again, char-promoting flame retardants are preferred, although bromine-containing, vapour phase-active surface treatments are effective. Horrocks (1986) has comprehensively reviewed developments in flame retardants for wool up to 1986 and very little has changed since that time. However, although considerable research has been undertaken into the use of functional phosphorus-based finishes, including the effectiveness of methylolated phosphonomides (e.g. Pyrovatex CP) (Hall and Shah, 1991), and substantive halogenated species like chlorendic, tetrabromophthalic anhydride (TBPA) and dibromo-maleic anhydrides and brominated salicylic acid derivatives, the most commonly used durable flame retardants are probably those based on Benisek's Zirpro (IWS) system (Horrocks, 1986). This treatment is applicable from the dyebath and has no obvious associated discoloration or affect on wool aesthetics.

The Zirpro process is based upon the exhaustion of negatively charged complexes of zirconium or titanium, usually as potassium hexafluorozirconate (K_2ZrF_6) or a mixture of this and potassium hexafluorotitanate ($K_2Ti\ F_6$), onto positively charged wool fibres under acidic conditions at a relatively low temperature of 60 °C. Application to wool is possible at any processing stage from loose fibre to fabric using exhaustion techniques either during or after dyeing; these have been fully reviewed and described elsewhere (Horrocks, 1986, 2003). The relatively low treatment temperature is an advantage because this limits the felting of wool and by maintaining a low pH (3), penetration is maximised and wash-fastness to as many as 50 washes at 40 °C or 50 dry cleaning cycles in perchloroethylene is achieved. The general simplicity of the whole process enables it to be used either concurrently with 1:1 premetallised and acid levelling dyes or after dyeing when applying acid milling reactive 1:2 premetallised and chrome dyes. Furthermore, Zirpro treatments are compatible with shrink-resist, insect-resistant and easy-care finishes.

It has been proposed that the Zirpro treatment enhances intumescent char formation (Benisek, 1971) although this view is not universally held (Beck *et al.*, 1976). However, its effectiveness in protective fabrics to flame and heat at high heat fluxes, is associated with the intumescent fibrous char structures generated. Because of heavy metal effluent problems, there has been pressure to identify alternatives and limited interest remains in sulphation with ammonium sulphamate (Lewin and Mark, 1997) followed by curing at 180–200 °C in the presence of urea which can give a 50 hard water wash-durable finish for wool fabrics with little change in handle. While there has been concurrent interest in the use of intumescents (Horrocks and Davies, 2000) no commercial exploitation has taken place.

Wool blends pose different challenges, because of the complexity of wool on the one hand and the specificity of flame retardants with respect to each blend component fibre on the other. In the absence of any back-coating treatment, acceptable flame retardancy of Zirpro-treated blends is obtainable in 85/15 wool/polyester or polyamide combinations. Such fabrics are ideal for aircraft and other seatings as well as heavier fire protective clothing and uniforms. For lower wool contents in blends and without the possibility of using alternative FR treatments, flame retardancy can be maintained only if some of the Zirpro-treated wool is replaced by certain inherently flame retardant fibres, except for Trevira CS polyester where antagonistic effects have been noted (Benisek, 1981). Chlorine-containing fibres such as PVC and modacrylics are particularly effective in this respect.

15.3.5 Flame retarded and inherently flame retardant synthetic fibres

Notwithstanding their associated thermoplasticity and often fusible behaviour (see Table 15.1), these fibres may, however, be used as minor components in blends with char-forming fibres, particularly cellulosic and wool and these have been discussed above. Rarely when present as a minor component are these synthetic fibres individually treated (Horrocks, 2003) and they rely on the flame retarded majority component to reduce any flammable tendency. Their presence is often included to enhance tear strength and abrasion resistance as well as conferring some easy-care character but their generally non-char-forming behaviour remains a problem, unless heavily back-coated (see section 15.3.6).

However, some synthetic fibres modified during production by either incorporation of a flame retardant additive in the polymer melt or solution prior to extrusion or by copolymeric modification can yield inherent flame retardancy, although still thermoplasticity remains a challenge. Perhaps the oldest available fibres in this group (see Table 15.3) are the modacrylics which have been commercially available for forty years or so although at present few manufacturers, such as the Kaneka Corporation of Japan and Montefibre in Italy (see Table 15.3) continue to produce them. These fibres have some char-forming capacity because of the comonomeric chloro-species present. It is this char-forming capacity that makes their presence in the previously mentioned Protex M blends with cotton so effective along with the ability of the chlorine radicals released by the Kanecaron Protex component to flame retard adjacent cotton fibres. Not surprisingly, therefore, the chlorofibres such as PVC and PVDC themselves (see Table 15.3) are highly char-forming and also belong to this group. However, because both these fibre groups have poor thermal physical properties and release hydrogen chloride gas during burning, they will not find application in closed environments such as exist in aircraft and other transport systems.

On the other hand, one group which continues to be successful is FR polyester (see Table 15.3) typified by the well-established Trevira CS (Horrocks, 1996), which contains the phosphinic acid comonomer. Toyobo's latest version of its Heim FR polyester is also based on a phosphorus-containing, phosphinate diester and this has claimed superior hydrolytic stability (Weil and Levchik, 2004). Other flame retardant systems, believed to be based on phosphorus-containing additives, such as Fidion FR (Montefibre) are also commercially available. However, these FR polyester variants do not promote char but function mainly by reducing the flaming propensity of molten drips normally associated with unmodified polyester. Thus they are rarely used in protective applications and only if blended with compatible flame and/or heat resistant, char-forming fibres as the major element.

15.3.6 Coatings and back-coatings

Coatings are applied to both sides of a fabric or impregnate the whole structure. Their general impermeability restricts their use unless associated waterproof properties are desired. Obviously, the use of the moisture-permeable coatings, typified by the microporous, copolymeric acrylics and polyurethanes (Woodruff, 2003) will improve their aesthetic and handle. Protective applications will include waterproof mattress coverings and tickings for use in hospitals as well as seating fabrics for contract furnishing and transport applications where the underlying filling must be protected from an impinging ignition source. The flame retarding elements within these coatings may arise from the use of flame retardant copolymers, typically vinyl or vinylidene chloride and/or the presence of additives in common with back-coating formulations. Back-coatings, however, are specifically applied to create flame retardant barrier properties only and they describe a family of application methods where the flame retardant formulation is applied in a bonding resin to the reverse surface of an otherwise flammable fabric. In this way the aesthetic quality of the face of the fabric is maintained while the flame retardant property is present on the back or reverse face. While the flame retardant components present are the major additives, careful use of viscosity modifiers and other proprietary chemicals ensures that 'grin-through' is minimised and that fabric handle is not compromised. Application methods include doctor blade or knife-coating methods and the formulation is as a paste or foam. These processes and finishes are used on fabrics where aesthetics of the front face are of paramount importance, such as domestic and contract furnishing fabrics where, again, ignition protection of the underlying filling material is of paramount importance.

Generally, the major flame retardants used are combinations of brominated organic species in synergistic combinations with antimony III oxide (Dombrowksi, 1996). The vapour phase activity of the typical Sb-Br flame retardants present ensures effectiveness of the finish if the coating is truly on the rear face of the fabric and they work well on all single and multifibre-containing fabrics independently of area density or construction. Most typical brominated derivatives are decabromodiphenyl oxide (DBDPO), and hexabromocyclododecane (HBCD) and while the former has just passed a European Risk Assessment and has been shown to be safe (Buszard, 2004), HBCD is still undergoing assessment. The present back-coating formulations based on these are very effective, can withstand defined cleansing processes such as the 30 min., 40 °C water soak defined in UK Furniture, and Furnishing (Fire) (Safety) Regulations (1988) (Consumer Protection Act, 1987) (see section 15.5) and are very cost effective. The recent environmental pressures to replace Sb-Br by less environmentally questionable retardants based on phosphorus (Horrocks, 2003) have not been successful to date and residual flame retardancy after a water soak treatment, often yields only marginal passes (Horrocks *et al.*, 2005). This is because not only do phosphorus-based retardants work in the condensed phase and so have difficulty transferring from the back to the front fabric face when exposed to a flame, but also they may be excessively water soluble.

Use of chlorine-containing resins, such as PVC-vinyl acetate and PVC-ethylene-vinyl acetate copolymers may decrease both the amounts of antimony-bromine additives as well as the less effective phosphorus-containing replacement retardants required and hence coating application levels themselves. For technical and economic viability, typical coating levels of 20–30% by weight are required and by careful formulating, passes to standard tests may be achieved.

15.4 Heat and fire resistant fibres and textiles

Heat resistant textiles comprise fibres that can withstand high working temperatures for reasonable service lives in applications like hot gas or fume filtration and where flammability is of secondary importance. Table 15.2 lists the more commonly available examples of these fibres with respective maximum service exposure temperatures. The limiting oxygen indices of these fibres are also included and it is evident that all are flame retardant to varying degrees with LOI values as high as 55 and 68 being possible with the semicarbon and polybenzoxazoles (PBO) respective examples. It may thus be said that these organic heat and flame resistant fibres may offer varying levels of fire resistance subject to the limit that all carbon-containing fibres and textiles eventually burn. However, extreme thermal protection is a desirable feature in applications such as furnace linings or hot component insulation in car exhaust catalysts or around combustion chambers in jet engines where working temperatures and occasional flash temperatures are in excess of 500 °C and even 1,000 °C in extreme circumstances. These are indeed extreme cases and component fibres must be inorganic such as glass, silica and alumina for many such applications. While fire resistance is an intrinsic feature of these inorganic fibres and textiles, their poor aesthetics limits their use to these extreme technical applications. However, glass-cored, organic fibre-wrapped yarns may be used in more conventional textile roles and examples do exist (Tolbert *et al.*, 1989) where such yarns have been used for barrier fabrics in furnishing applications.

Selected examples of these heat and flame resistant fibres have been reviewed rigorously elsewhere (Horrocks *et al.*, 2001; Perepelkin, 2001), but their particular relevance to thermally protective textiles is more fully explored below. The main groupings of these fibres may be divided into the following groups, namely, the thermosets, the aramids and arimids, the polybenzazoles and the semicarbons. Not only are the generic chemistries similar within each grouping, but their properties and potential application suitabilities are similar.

15.4.1 Thermoset polymeric fibres

These are typified by the melamine-formaldehyde fibre Basofil (BASF) and the phenol-formaldehyde (or novoloid) fibre Kynol (Kynol GmbH) and have the common feature that when heated, they continue to polymerise, cross-link and thermally degrade to coherent char replicas. These chars have especially high flame and heat resistance as a consequence of their high carbon contents. In fact under controlled heating, novoloid-derived fibres can give rise to carbon fibres in their own right. While the parent polymers are cross-linked and not fibre-forming in the manner that linear polymers tend to be, they do give rise to fibres having acceptable textile properties. Their respective properties are listed in Table 15.4 from which it is seen that they have quite low strengths that prevent their being processed easily into yarns. Thus they are more often incorporated into nonwoven fabric structures. Furthermore, because each has an inherent colour, they are usually used as a barrier fabric and not in face fabrics. However, the melamine-formaldehyde structure in Basofil does allow the fibre to be dyed if small molecular disperse dyes are used under high-temperature applications similar to those used for polyester. Dyeing of Kynol is not possible. Both fibre

Table 15.4 Selected properties of melamine-formaldehyde (Basofil) and novoloid (Kynol) fibres

Property	Basofil (BASF)	Kynol (Kynol GmbH)
Tenacity, N/tex	0.2–0.4	0.12–0.16
Modulus, N/tex	6	2.6–3.5
Elongation-at-break, %	15–20	30–50
Moisture regain (at STP), %	5	6
Colour	Pale pink	Gold

types have relatively high moisture regains for synthetic fibres and so have desirable moisture transfer properties.

Respective thermal properties are listed in Table 15.2, and this indicates very similar properties with high levels of heat and flame resistance and complete freedom from any melting and dripping, unlike conventional synthetic fibres. Typical end use applications of both Basofil® and Kynol in thermal protection include fire blocking and heat insulating barriers or blockers and heat and flame protective apparel. Fibres may be blended typically with meta- and para-aramid fibres to improve tensile properties including strength and abrasion resistance in both nonwoven felts and fleeces for fire blocking aircraft seat fabrics and firefighters' clothing for example. For workwear, blending Basofil with inherently flame retardant viscose is also possible as this reduces cost, improves aesthetics and comfort and enables lighter fabrics to be constructed. However, Kynol is often favoured in heavier applications including outer and inner fabrics for firefighters' and racing drivers' clothing, hoods and gloves. Such fabrics may be aluminised to improve heat reflection and hence fire performance.

Both fibre types are reported to have low or even negligible emissions of smoke and toxic gases, such as carbon monoxide and hydrogen cyanide, when subjected to a flame and so find application in closed environments typically in transport, e.g., aircraft, cars, trains, ships, and even submarines. In public buildings they are also of use as fire blockers in furnishings, seat linings, smoke barriers and curtains.

15.4.2 The aramid and the aramid family

This group is perhaps the most well known and exploited of all the inherently heat and flame resistant fibres developed since 1960. They are typified by having aromatic repeat units bonded together by strong amide – CO.NH-, imide – CO.N< groups or both in alternating manner. In polyaramids the single C–N bond in the amide group determines thermal resistance, whereas in polyimides, this same C–N bond is strengthened by the presence of increased conjugation and so the former have inferior heat resistances to polyarimid analogues as will be shown below. However, all members of this group are typified by having thermal resistances in excess of 300 °C for short-term exposures and high levels of inherent flame resistance (see Table 15.2).

The most commonly used thermally resistant aramids are based on a meta-chain structure as typified by the original Nomex (Du Pont) fibre introduced over 40 years ago. Typically, these commercially available fibres are based on poly (meta-phenylene isophthalamide), with other brands being available, e.g., Conex (Teijin), Apyeil (Unitika) and Fenilon (former USSR), in addition to modifications having modifed tensile properties (e.g., Inconex, Teijin) and antistatic properties (Apyeil-α, Unitika). Over the years, these fibres have become available with improved dyeing properties and so are now available in full colour ranges. Their advantage over many other thermally resistant fibres is their acceptable tensile and physical properties that are very similar to those of conventional nylons 6 and 6.6, hence they are often claimed to have an overall more acceptable textile performance. Their rigid, all-meta aromatic polymer chains ensure that the fibres have minimal thermoplastic characteristics with second-order transition temperatures (T_g) of about 275 ºC and an ill-defined melting point accompanied by thermal degradation starting at 375 ºC (see Tables 15.1 and 15.2). These enable the fibres to be used in textiles where shrinkage should be minimal at temperatures of continuous use of 150–200 ºC and to shorter exposures as high as 300 ºC and so are ideal for use in protective clothing. LOI values are 28–31 and so they compete effectively with many other non-thermoplastic flame retardant fibres such as flame retarded cotton and wool, which have similar LOI values, although they are inferior to the highly cross-linked (e.g. Kynol), semicarbon and polybenzazole groups of fibres.

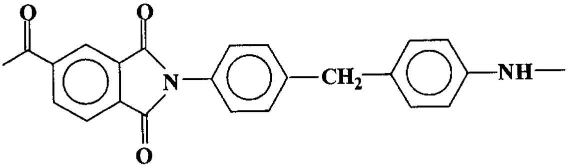
In order to improve the performance of the meta-aramids, Du Pont in particular, has introduced a number of variants over recent years. For example, blending with small amounts of para-aramid fibres (e.g. Nomex III contains 5% Kevlar) enables the thermal protective behaviour to increase primarily through increasing the char tensile strength. Nomex III is available in a limited range of spun-dyed colours and is recommended for applications where direct heat exposure is possible, e.g., single or multi-layer garments such as firefighters' station uniforms, coveralls, jackets, trousers, gloves, flight suits or tank crew coveralls. Nomex Comfort incorporates microfibre technology and has improved antistatic and moisture management properties and is recommended for coveralls, foul-weather gear, fleece, shirts, hoods and a range of knitwear fabrics including T-shirts and underwear. A third variant is Nomex Outershell, specifically designed for firefighters' clothing although it may be used in other suggested applications for Nomex III.

There have also been attempts to reduce costs by blending meta-aramids with lower cost flame retardant fibres like flame retardant viscose. Thus Du Pont introduced the fabric Karvin, comprising 30% Nomex, 5% Kevlar para-aramid and 65% Viscose FR (Lenzing). While having similar flame retardancy to their respective parent single aramid components, their char structures are weaker and so do not offer sustained fire protection at high heat fluxes and temperatures as the 100% meta-aramid fabrics do. However, recent work has indicated that use of aramid blends may offer overall advantageous properties and this is exemplified by research at ENSAIT in Lille, France which has shown that the fire performances of wool/para-aramid blends containing over 30% and up to 75% para-aramid are superior to that for 100% para-aramid measured in terms of reduced peak heat release rate from cone calorimetry (Flambard *et al.*, 2005).

The para-aramids are typified by Kevlar (DuPont) and Twaron (Teijin) and are based on poly (para-phenylene terephthalamide). While having enhanced tensile strengths and moduli as a consequence of the extreme symmetry of their polymer chains and hence order or crystallinity, they also have enhanced thermal performance. The increased structural chain rigidity and order raises the second-order transition temperature to about 340 °C and melting point to about 560 °C before decomposing above 590 °C (see Table 15.1). Furthermore, higher continuous working temperatures of 180 °C and above are possible with resistance to short-term exposures to temperatures as high as 450 °C being achievable (see Table 15.2). However, thermal degradation is similar to that occurring in the meta-aramids and so the LOI values are similar at 30–31%. However, the higher cost, poorer textile processing properties and higher modulus of para-aramid fibres ensure that their use in applications such as protective textiles are limited to 100% contents only when performance demands are exceptional. Thus, and as is more usually the case, additions of small amounts of para-aramid to blends with meta-aramid (e.g. 5% in Nomex III) and blending with other cheaper flame retardant fibres offer enhanced improved tensile and heat and flame resistance relative to the major fibre present.

With regard to arimid fibres, while a number have been reported and reviewed (Raheel *et al.*, 1994; Horrocks *et al.*, 2001), only the example P84 introduced by Lenzing during the mid-1980 period has been commercially exploited. P84 fibres are now produced by Inspec Fibres (USA). As Table 15.2 indicates, these fibres have superior thermal properties to aramid and so find use in protective applications. For example, outerwear, underwear and gloves may be made from 100% P84 or blended with lower cost fibres like flame retardant viscose. For instance, a 50/50 P84/Viscose FR (Lenzing) blend is used for knitted underwear with high moisture absorbency. Alternatively, blending with high tenacity polyaramids increases wear and tensile characteristics. Spun-dyeing of P84 fibres enables their natural gold colour to be replaced by those often demanded by customers who may require more appropriate bright safety colours.

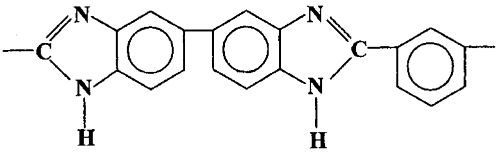
The final member of this grouping is the poly (aramid-arimid) fibre, Kermel, which was produced initially by Rhone-Poulenc of France in 1971 and is now produced by Rhodia Performance Fibres. The chemical structure of Kermel is a combination of amide –CO.NH- and imide –CO.N< functional chain groups.



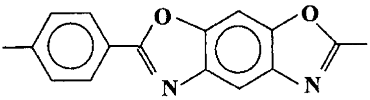
While its overall properties are very similar to those of the meta-aramids, it shares certain problems including difficult dyeability although in 1993, a so-called third-generation Kermel was announced which claimed to have superior colouration properties. Like the poly (meta-aramids), however, Kermel has poor UV stability, and so must be protected from intense radiation sources. Its second-order and decomposition temperatures fall between those of the para-aramid and the arimid fibre P84 (see Table 15.2) and this reflects the lower chain rigidity and the weaker polyamide bond structure. With an LOI value of about 32%, comparable to the meta-aramids, it competes in protective clothing markets where again it is used as 100% Kermel or as blends with other fibres, including FR viscose. Blends with wool have been shown to be ideal for uniforms, jerseys and pullovers. Production of composite yarns with high modulus aromatic fibres like the poly (para-aramids) has yielded the modification Kermel HTA, a yarn with a para-aramid core (35%) and a Kermel fibre wrapping (65%). Not only does this yarn enable the aesthetics and colour of the outer fibres to be prominent, but also like Nomex III discussed above, the para-aramid content enables the strength and abrasion resistance fabrics to be increased.

15.4.3 Polybenzazole group – polybenzimidazole and polybenzoxazole fibres

These fibre-formimg polymers are so-called 'ladder polymers' and essentially have wholly aromatic polymer chains. The two common examples available commercially are the polybenzimidazole PBI (Celanese) with the chemical structure:



and full chemical name poly (2,2′-(m-phenylene)-5,5′-bibenzimidazole) and the polybenzoxazole, Zylon (Toyobo) with the structure:



and full chemical name poly(para-phenylene benzobisoxazole) and generic acronym, PBO. The similarity in general polymer chain structures is apparent and it is the high degree of chain rigidity that gives both of these fibres their superior thermal properties as shown in Table 15.2. Both fibres have thermal degradation temperatures well in excess of 400 °C and can operate at continuous temperatures of well over 200 °C and demonstrate superior LOI values well over 40%.

PBI has been introduced to the commercial markets only during the last 20 years or so in spite of its development during the early 1960s. It was then that the US Air Force Materials Laboratory (AFML) contracted with the former Celanese Corporation to develop a novel high-temperature resistant fibre. In the aftermath of the 1967 Apollo spacecraft fire, AFML and NASA examined PBI fibre as a non-flammable material for flight suits that would afford maximum protection to astronauts in oxygen-rich environments. Subsequently, in 1983, Celanese built a full-scale manufacturing plant for the production of PBI polymer and fibre to develop civilian markets.

The current PBI fibre is a sulphonated version of the chemical formula above and this improves shrinkage resistance at high temperature. The fibre has a moderate strength of about 0.25–0.30 N/tex, a lowish modulus of about 3 N/tex and a remarkably high moisture regain of 15%. It is easily processible by normal textile methods and gives rise to very comfortable fabrics, although the inherent colour is bronze-like or even gold in some forms. The fibre cannot be dyed and it is often blended. One well known blend is PBI Gold in which a yarn spun with both PBI and Kevlar in a 40/60 blend that gives rise to gold-coloured fabrics with fire protective properties claimed to be superior even to those made from Nomex III. Presently, this blend is being introduced into firefighters' clothing both in the USA and UK. This includes outershells as well as underwear, hoods, socks and gloves. Other uses include industrial workwear, aluminised proximity clothing, military protective clothing and fire barrier/blocker applications. However, PBI is several times as expensive as the meta-aramids and so this superior performance comes at a price.

Zylon or PBO is a more recently developed fibre than PBI and has outstanding tensile properties as well as superior thermal and fire properties to any of the fibres mentioned in this section (see Table 15.2). Its tensile strength is well above 3 N/tex and modulus exceeds 150 N/tex, both values being about twice respective values for Kevlar. While there are at least two variants of fibre, Zylon-AS and Zylon-HM of which the latter has the higher modulus, they both have these same thermal and burning parameter values. The fibre is available in staple, filament and chopped forms and finds applications in the area of thermal and fire resistance products where a combination of these with high tenacity and modulus are required. Principal examples of thermally protective textiles include heat protective clothing and aircraft fragment/heat barriers. The price of this fibre is probably similar to that of PBI and so its use is restricted to applications where strength, modulus and fire resistance are at a premium.

15.4.4 Semicarbon

The semicarbon fibres include any in which the structure is essentially carbon while retaining acceptable textile properties, unlike true carbon fibres (Hearle, 2001). Within the group, the oxidised acrylics represent the sole commercial group and are produced following controlled high-temperature oxidation of acrylic fibres during the first stages of carbon fibre production. First reported about 1960 as 'Black Orlon' (Vosburgh, 1960), they became of commercial interest as potential high-temperature-resistant fibres during the early 1980s.

During this period a number of commercial versions were announced including Celiox (Celanese), Grafil O (Courtaulds), Pyron (Stackpole), Sigrafil O (Sigri Elektrographit, now SGL) and Panox (SGL UK Ltd., formerly R K Textiles). There are presently large production plants for oxidised acrylics in North America, UK, France, Germany, Hungary, Israel, Korea, Taiwan and Japan.

The fibres have only a low tenacity at about 0.15–0.22 N/tex, a moderate extensibility of 15–20% and a reasonable modulus of 5–8 N/tex. This creates the problem of ease of processability for these weak fibres although they can be spun into yarns by the woollen system. Thus they are produced as a continuous tow that is stretch-broken by conventional means for eventual conversion into coarse woollen-type yarns, although fine filaments of the order of 1.7–5 dtex are possible. The surprisingly high moisture regain of 10% enables fabrics to have an unexpected comfort. The limiting oxygen index is typically about 55% and so fabrics are extremely thermally resistant giving off negligible smoke and toxic gases when subjected to the even the most intense of flames. Unfortunately, of course, the fibres are black and so are rarely used alone except in military and police coverall clothing where the colour is a bonus. More usually, oxidised acrylic fibres are blended with other fibres, typically wool and aramid in order to dilute the colour and introduce other desirable textile properties. Because of their extreme fire resistance and lower cost than PBI and PBO, they find applications usually as blends in anti-riot suits, tank suits, FR underwear, fire blockers for aircraft seats and heat resistant felts (insulation), hoods and gloves. When aluminised, they are very effective in fire entry/fire proximity suits. More specialist end-uses include fabrics for protection against phosphorus and sodium splash and welding blankets. Usually, however, other finishes to reduce fabric permeability are essential if full protection, say, against petrol or molten liquids is to be afforded. Finally, fabrics may be overprinted to offset the underlying natural colour.

15.5 Design Issues

15.5.1 Maximising flame, heat and fire resistance

The factors that determine maximisation of fire resistance in a given textile product lie primarily in the properties of the fibre and fabric characteristics for each component. These include the thermal inertia of the fabric (Day and Sturgeon, 1987) and the abilities to reflect radiant thermal energy and to insulate the underlying surface (or wearer) from the incident fire or thermal source (Krasny, 1986). Heat reflective treatments such as aluminisation are use effectively in both fire protective clothing and fire blocker applications. Thermal inertia and insulative character are both related to fabric weight or area density, although heavier fabrics become more uncomfortable in hot environments. In addition, air permeability, moisture and construction can influence thermal behaviour with nonwovens tending to give superior properties to wovens or knitted structures, all other variables being equal (Lee and Barker, 1987). Baitinger (1979), however, suggests that only at low levels of heat exposure do physical variables like thickness correlate with insulative properties, whereas it is the fibre type and finish and respective degradative resistances that determine high heat exposure performance. Essentially, this means that it is the ability of a fabric assembly to retain its thickness when subjected to a heat flux, whether radiant, convective or both (Shalev and Barker, 1986).

Most thermally protective textiles have area densities in excess of 250 gsm or so with workwear and the lighter upholstery and barrier fabrics being in the 250–350 gsm range. However, it is the air trapped within the interstices of any fabric structure and between layers of fabrics within a garment assembly that provides the real thermal insulation. The need to have thermal and fire resistance in the component fibres ensures that these insulating air domains are maintained. Any slight tendency of a garment to shrink will reduce its insulative effectiveness, even if the fibres present remain undamaged. It goes without saying, therefore, that the presence of any thermoplastic fibre is to be avoided and in fact banned from use in certain applications. However, while the essentially non-thermoplastic fibres, both natural and synthetic, described above and which feature in Tables 15.1 and 15.2 are generally assumed to have negligible shrinkage at elevated temperatures, at very high temperatures even small levels may cause concern. Barker and Brewster (1982) have published shrinkage data at 300 °C where charring is minimal and at 400 °C where it may be considerable in some fibres. For instance, even FR cotton shows 25–29% shrinkage at 300 °C increasing to about 40% as it chars at 400 °C. Nomex aramid is shown to give 0% at 300 °C and yet 5–12% at 400 °C. Kevlar aramid shows 0% at both temperatures thus demonstrating why it is introduced into Nomex III. Even PBI shows a measurable shrinkage of 2% at 300 °C rising to 6% at 400 °C.

However, even with the most fire resistant fibres present, no single fabric can perform all the tasks required of it in a given product and many garments and clothing assemblies are multilayered and may consist of a set of components to form a system. While a protective fire resistant coverall or item of workwear may be a single-layered garment comprised of the most cost-effective fabric that has the desired level of protection, underneath may be the requirement for fire resistant linings and underwear, including socks and gloves in order to provide full and fail-safe protection. For example, a very recent study (Valentin, 2004) has compared the performance of three competing designs of firefighters' outer jackets comprising external and liner fabrics in the following combinations:

- meta-aramid/para-aramid blended external fabric plus knitted modacylic-polyurethane membrane-meta-aramid felt/FR viscose composite liner
- meta-aramid/para-aramid blend-polyurethane membrane-meta-aramid nonwoven external fabric composite plus a liner comprising a meta-aramid/FR viscose blend with para-aramid spacers

- meta-aramid/para-aramid nonwoven blend with para-aramid spacers/PTFE membrane external fabric assembly plus meta-aramid felt/FR viscose liner.

It is noteworthy that each of these has an outer fabric containing meta- and para-aramid blends for good fire protection and durability. However, a number of inner layers, whether joined to the outer or part of the liner comprising breathable polyurethane or PTFE membranes, are also a common feature. Thirdly, the use of thermally insulative nonwoven interlayers and comfortable meta-aramid/FR viscose innermost linings are also present. It is the ordering and exact interlayer compositions that appear to be the major differences while each design attempts to provide the common properties of fire resistance, thermal insulation, moisture transport and comfort.

Anticipated wearing times may also influence design because some coveralls or outershells may be required to be worn only as an emergency garment over normal working clothes which may be fire resistant or not, as the case may be. However, the more complex coveralls and jacket/trouser assemblies may be required to be worn for a full working period or, indeed, more extreme lengths of time in some firefighting, military and civil emergency environments. Furthermore, in addition to fire resistance may be the requirement of resistance to water (e.g. firefighters' outershells), petrol (e.g. police anti-riot gear) and other aggressive agencies (e.g. chemical and biological threats). In some cases, a multi-functional character will be an essential feature. However, in the main, fire resistance is the first concern that requires an effective heat and flame resistant base fabric to be designed to which surface finishes, coatings or other treatments may be applied to yield all the desirable properties.

The exposure time of a particular fire and related threat is of considerable importance in choosing the base fabric. For example, in workwear where fire resistance is a low to medium risk (e.g. chemical workers' overalls), flame retardant cotton or viscose fabrics are ideal compositions and exposure to a fire hazard will prevent outer garment ignition for a limited period. Furthermore, the char formed following exposure will provide a degree of further protection while the victim escapes from the fire hazard. However, if the fire risk is high and there is a need to provide an increased escape time, then fabrics will be constructed from the higher performance fibres such as the aramids, arimid, aramid-arimid, PBI, PBO, semicarbon, etc. Here charring occurs much more slowly and outer garments retain their integrity for periods of many minutes even in intense fire environments that firefighters and racing drivers experience, for example.

It is important to realise, however, that a working human cannot survive for very long without oxygen and so even the most fire-resistant garments will not protect for long unless suits such as fire proximity and racing car drivers suits are fitted with internal oxygen or air breathing supplies and smoke and heat masks. Even if the immediate threat is not so great as to need this requirement, then the ability to work efficiently in a hot, high-risk environment for considerable periods of time is an important concern – this is the typical firefighters' scenario.

Similar issues are important in fire blocking fabrics from simple furnishing fabrics that in the UK must resist a simulated match and cigarette ignition, to those used in aircraft seating that must resist the US Federal Aviation Administration kerosene burner test FAR 25.853(c). In the latter a full seat mock-up is exposed to a burner with a heat flux of 115 kW/m^2 for 120s and fabric/seat assemblies must suffer a weight loss of less than 10%, fall within specified maximum and average burn length criteria as well as not sustaining afterburning and smouldering for more than five minutes. Fire blockers that enable passes to be achieved may have a variety of weights depending on whether aluminised and the choice of fibres present. For instance, fabrics comprising Zirpro wool, oxidised acrylics, aramid, arimid and glass in various blends and in woven or nonwoven structures with area densities from 250–400 gsm are typically used.

One final thermal threat requiring specialist textile solutions is that of molten metal splash where temperature, metal density, size of splash droplets and droplet surface reactivity determine the solution to be adopted. These factors are all different for molten iron or steel, copper, tin, lead, zinc or aluminium and so protective aprons and overalls have to be tailored to fit the threat. Issues here are whether or not:

- the temperature of the molten metal drop is sufficient to ignite the fabric
- the density and hence mass of a drop enables the drop to 'burrow' into the textile as it chars the underlying fibres
- the drop sticks or slides from the fabric surface.

Traditionally, furnace operators have always worn leather aprons which are heavy and uncomfortable. Heavy metal processing, e.g., steel, iron, lead and copper, requires heavier fabrics to offset the effect of burrowing and flame retarded wool and cotton fabrics with area densities in the range 260–660 gsm have been shown to be superior to 100% aramid, novoloid and glass fabrics. Their effectiveness is partly related to the excellent char-forming abilities of cotton and wool although the intumescent charring character if wool is generally believed to explain its overall superior properties in this respect (Benisek and Edmondson, 1981). For Zirpro-treated wool, it was noted that the degree of damage decreased in the order: iron, copper > aluminium, zinc > lead, tin. The advantageous effect of aluminised surfaces and use of ceramic fibres in improving resistance to molten iron was noted by Barker and Yener (1981). However, one real problem is that posed by aluminium, which, because of its reactive surface, sticks to many flame retardant fabrics, including aramids and glass, although it does not do so to Zirpro-treated wool and untreated cotton (Benisek and Edmondson, 1981). This effect is compounded by the low density of aluminium and so droplets do not have the mass to break away from the surface fibres on the fabric.

15.5.2 Maintaining comfort and aesthetics

Heat fatigue is as much a hazard to the firefighter as the fire itself to a large extent and is a major consideration in designing clothing assemblies (Holmér, 1988). Thus, while having a high level of protection afforded by his or her firefighting suit, the wearer must be able to wear it for long enough to do an effective job while ensuring that comfort is acceptable and that moisture loss is minimised to prevent dehydration. Thus, while offering fire and water protection, the outer shell should be breathable and the inner lining assembly should enable moisture to be wicked away from the body and underclothing. This same lining should have an appropriate level of fire resistance should the outer shell be damaged. However, for every slight increase in the clothing weight, so the risk of heat fatigue is increased and so a compromise situation is reached as the clothing system becomes more complex in structure. Underclothing should, therefore, enable both heat and moisture to be transmitted away from the body, air gaps should be maintained and there should be no chance of shrinkage of any part of the garment assembly.

In the case of fire blocker fabrics used in seating assemblies, the flexibility and aesthetics of the face fabrics should not be compromised by their presence. This is a particular issue in both contract furnishings in the UK that require ignition resistance to more intense sources than matches and cigarettes (see BS 7176:1995 in section 15.5) and in aircraft seating where passengers may be sitting continuously for considerable periods.

15.5.3 Combining other properties

The need for multifunctionality in thermally protective textiles is becoming increasingly a necessity for many applications. Table 15.5 lists typical requirements and possible solutions. Often when multifunctionality is required, competing effects and finishes may cancel unless carefully engineered. Furthermore, such treatments must not add to the potential flammability of the overall textile. For instance, water repelling characteristics demand hydrophobic coatings or finishes while oil and petrol require hydrophilic treatments. Luckily, with the advent of the very low surface energy fluorocarbons (Holme, 2003), both goals may be achieved providing fibre surfaces are clean and inherent flammability properties are low or negligible. Not only do these fluorocarbon finishes produce both water and oil repellency but also offer soil release characteristics that ensure fabrics remain cleaner for longer. Thus from conventional UK domestic flame retardant furnishings to the more sophisticated firefighters' outershell, the presence of fluorocarbon treatments is common.

Table 15.5 Typical multifunctional requirements and solutions for thermally protective textiles

Function	Solution	Reference
Moisture transport and management	Microporous membranes and coatings	Holmes, 2000; Holme, 2003; Woodruff, 2003
Oil and petrol repellency	Fluorocarbon finishes	Holme, 2003
Water repellency and proofing	Breathable coatings	Holme, 2003; Woodruff, 2003
Ballistic properties	Inclusion of high modulus fibres	Hearle, 2001; Scott, 2000
Chemical resistance	Impermeable barriers (e.g. PTFE, PVC, neoprene) Adsorptive barriers (e.g. active carbon)	Raheel, 1994
Microbiological resistance	As for chemical resistance plus use of antimicrobial fibres	Vigo, 1994
Radioactive particle resistance	As for chemical resistance	Raheel, 1994; Scott, 2000
Colour, camouflage, radar signature	Dyestuff and colourant selection	Scott, 2000

The need for cleanliness also influences the effect of other properties, not least flame retardancy when small amounts of oily soil may offset the flame retardant character of the underlying textile. While it is assumed that all flame retardant finishes used in protective textiles have the desired level of laundering durability (Horrocks, 1986, 2003) and those containing inherently FR fibres have very high levels, laundering itself can cause deposits of water hardness salts and detergent residues that may increase ignitability. Thus, sophisticated protective textiles from which sustained high levels of performance are demanded often have stringent aftercare instructions issued with them. This is the case with aircraft and transport seatings, firefighters' clothing assemblies and protective clothing for military personnel (Scott, 2000).

15.6 Testing and performance

The details of the many test methods available across the world are outside the scope of this chapter, although Eaton (2000) has recently reviewed those more relevant to the UK. Most test methods are defined by a number of national and international bodies such as air, land, and sea transport authorities, insurance organisations and governmental departments relating to industry, defence and health, in particular. While the reader is recommended to refer to the indexes of major standards institutions such as the British Standards Institution (BSI) and the American Society for Testing and Materials (ASTM), normalisation across the European Union during the last ten years or so has seen traditional 'BS' tests replaced by BS EN and BS EN ISO alternatives as methods of test become truly international. For a detailed examination of most of the world's test methods relating to textiles and plastics materials, the reader should consult Troitzsch (2004).

Because textiles are 'thermally thin' and have high specific volumes and hence accessibility to oxygen from the air and these properties are determined by variables in yarn, fabric and product geometries, textile tests usually focus only on ease of ignition and/or burning rate behaviour which can be easily quantified for fabrics and composites in varying geometries. Few, however, yield quantitative and fire science-related data unlike the often criticised oxygen index methods (Horrocks *et al.*, 1987).

15.6.1 Textile component testing

Most tests for protective textiles examine and test the potential ignition resistance and ability of single fabrics or eventual product components to protect underlying surfaces or materials. These tests may be undertaken on a single fabric or a composite that reflects a real application or product. Table 15.6 lists a selection of tests useful in the thermal and flammability assessment of protective textiles. In all flammability test procedures conditions should attempt to replicate real use and so while atmospheric conditions are specified in terms of relative humidity and temperature ranges allowable, fabrics should be tested after having been exposed to defined cleansing and aftercare processes. Table 15.6 includes BS 6561 and its CEN derivatives as being typical here and these standards define treatments from simple water soaking, through dry cleaning and domestic laundering to the more harsh commercial laundering processes used in commercial laundries and hospitals, for instance.

While simple vertical strip tests such as the now discontinued BS 6249:Part 1:1982 originally used for assessing flame retardant workwear performance are still well-established in other areas of textiles, they are embedded within the more recent European tests for protective clothing also listed in Table 15.6. Thus BS 6249, which uses the established standard test method BS 5438, has been replaced by the general performance standard BS EN 533:1997 in which BS EN 532:1994 is the test method (see Fig. 15.1).

Tests for furnishing fabrics and blockers as barriers

When assessing the ability of a furnishing fabric to resist ignition and protect the underlying filling, BS 5852 Parts 1 and 2:1979 and its subsequent EN and BS

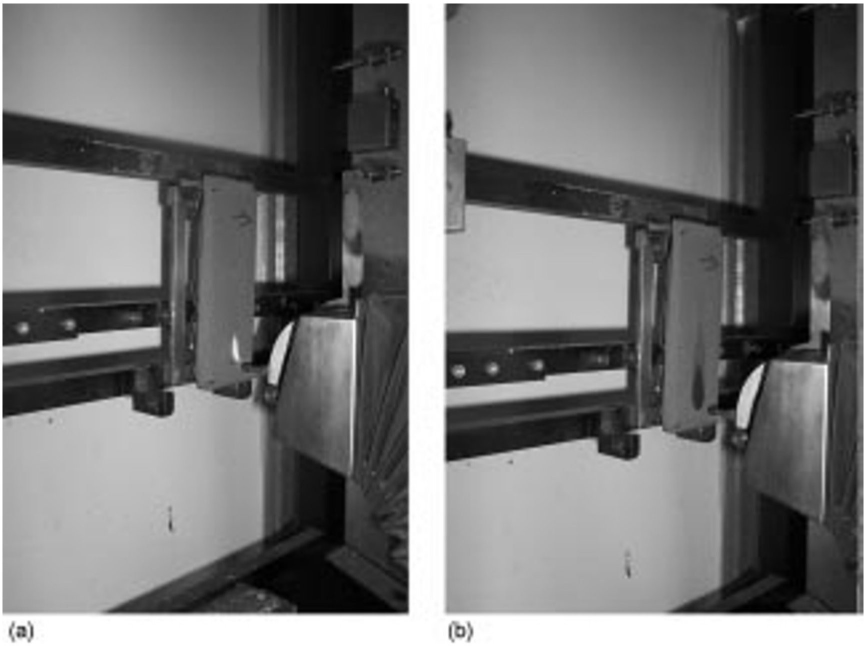
Table 15.6 Selected test methods for protective textiles

Nature of test	Textile type	Standard	Ignition source
British Standard based vertical strip method BS 5438	Protective clothing (now withdrawn)	BS 6249:Part 1:1982 (replaced by BS EN 533:1997)	Small flame
ISO vertical strip similar to Tests 1 and 2 in BS 5438	Vertical fabrics	BS EN ISO 6940/1:2004	Small flame
Small-scale composite test for furnishing fabrics/fillings /bedding materials	Furnishing fabrics	BS 5852: Pts 1 and 2:1979 (retained pending changes in legislation)	Cigarette and simulated match flame (20 s ignition)
	Furnishing fabrics	BS 5852:1990(1998) replaces BS 5852: Pt 2	Small flames and wooden cribs applied to small and full-scale tests
		ISO 8191:Pts 1 and 2 (same as BS 5852:1990)	
		BS EN 1021-1:1994	Cigarette
		BS EN 1021-2:1994	Simulated match flame (15 s ignition)
Cleansing and wetting procedures for use in flammability tests	All fabrics	BS 5651:1989	Not applicable but used on fabrics prior to submitting for standard ignition tests
	Commercial laundering	BS EN ISO 10528:1995	
	Domestic laundering	BS EN ISO 12138:1997	

Table 15.6 Continued

Nature of test	Textile type	Standard	Ignition source
Protective clothing	General requirements	EN 340	
	Resistance to radiant heat	BS EN ISO 6942:2002 (formerly BS EN366:1993 which replaced BS 3791:1970)	Exposure to radiant source
	Resistance to convective heat (flame)	BS EN 367:1992	Determine heat transfer index
	Resistance to molten metal splash	BS EN 373:1993	Molten metal
	Gloves	BS EN 407:1994*	Composite standard (including firefighters' and welders' gloves)
	Firefighters' clothing	BS EN 469:1995*	Composite standard
	Welders' and allied industrial clothing	BS EN 470-1:1995/ISO 11611	Composite standard
	General flame spread	BS EN ISO 15025:2002 (formerly BS EN 532:1995 which replaced BS 5438)	Small flame
	Workers exposed to heat	BS EN 531:1995/ISO 11612	Composite standard
	General protection	BS EN 533:1997* (replaces BS 6249)	Small flame
	Contact heat transmission	BS EN 702:1995	Contact temps. 100–500 °C
	Firefighters' hoods	EN 131911	

Note: * Test methods presently under review.



15.1 Flame retarded cotton being tested to the BS EN 532 test method; (a) shows the flame application and (b) shows the char after igniting flame extinction (courtesy of Rhodia Consumer Specialities, Oldbury, UK).

EN editions combine both the test method and performance-related set of defining criteria. With the recognition of the hazards posed by upholstered fabrics, the development of the small-scale composite test BS 5852 in 1979 represented a milestone in the development of realistic model tests which cheaply and accurately indicate the ignition behaviour of full-scale products of complex structure. One major strength of this test is that it defines a set of different ignition sources from the cigarette, through a series of gas burners of increasing intensity to a series of wooden cribs in a total order of increasing thermal output to represent real ignition source intensities. In the UK, BS 7176:1995 specifies which source should be used for furnishing fabrics in environments of increasing ignition hazard and Table 15.7 summarises these. A similar advisory standard for testing bedding over a non-combustible fibre mat is defined in the sister standard BS 7175 and its related test methods for ignitability of mattresses of divans using sources in BS 5852 (BS 6807:1996 and ISO 12952-1/4:1998), but this is outside the present discussion for protective textiles.

Fire barrier or blocker fabrics are usually tested under conditions that realistically attempt to replicate their application thermal hazard. A prime example is the kerosene burner test used to test commercial aircraft seating, FAR 25.863(c), discussed above. In other cases, where a blocker is part of a larger system such as part of a building or transport system, then the test will be

Table 15.7 Ignition source/hazard combinations – BS7176: 1995 (for full details, see the actual standard)

	Low hazard	Medium hazard	High hazard	Very high hazard
Requirements	Resistance to ignition source: smouldering cigarette of BS EN 1021-1:1994 and the match flame of BS EN1021-2:1994	Resistance to ignition source: smouldering cigarette of BS EN 1021-1:1994 and the match flame of BS EN1021-2:1994 Resistance to ignition Source 5 in BS5852: 1990	Resistance to ignition source: smouldering cigarette of BS EN 1021-1:1994 and the match flame of BS EN1021-2:1994 Resistance to ignition Source 7 in BS5852: 1990	Resistance to ignition source: smouldering cigarette of BS EN 1021-1:1994 and the match flame of BS EN1021-2:1994 At discretion of the specifier but at least high hazard requirements
Typical examples	Offices Schools Colleges Universities Museums Exhibitions Day centres	Hotel bedrooms Public buildings Restaurants Places of public entertainment Public baths Public houses & bars Casinos Hospitals Hostels	Sleeping accommodation in certain hospital wards and hostels Off-shore installations	Prison cells

related to the related building, motor vehicle, rail vehicle, aircraft or ship fire testing regime (Troitsch, 2004). While building fire tests relate to national standards requirements, for aircraft and ships, there are overarching agencies responsible for these tests with international standing such as the US Federal Aviation Administration (FAA) and the International Maritime Organisation (IMO). For further details into this complex area, the reader is referred to Troitzsch (2004) and relevant organisational web-sites.

Protective clothing tests

Table 15.6 shows also a set of tests which has recently been developed across the EU to accommodate the different demands of varying types of protective clothing and hazards, whether open flame, hot surface, molten metal splash or indeed a combination. For test details, the author is referred to the specific method but it is significant to note that for a fabric to be used in a given defined protective clothing end-use, general ignition resistance and flame spread tendency (test method BS EN 532:1994 and performance requirement BS EN 533:1997; see Fig. 15.1) will complement more application-specific requirements such as resistance to radiant (BS EN ISO 6942:2002) and convective (flame) (BS EN 367) heat or hot metal splash (BS EN 373:1993).

While it goes without saying that most protective clothing must pass a simple ignition and flame spread test such as BS EN 532, of particular relevance to thermally protective clothing and an area that has seen much research activity is that of heat transfer and the ability of a given fabric or layered assembly to minimise heat transmission to a wearer. Tests like BS EN 367 measure a heat transfer index (HTI) and this has developed from a history of similar measures of the ability of a fabric to insulate the wearer. These indices are usually measures of times to achieve a given burn level (Shirley Institute, 1982; Barker and Coletta, 1984). For example, Benisek and Phillips (1981) showed that the time taken for the temperature to reach a second-degree burn level behind a given protective textile fabric exposed to an open-flame, convective heat source was in the increasing order FR cotton (315 gsm) < Aramid (259 gsm) < Zirpro wool (290 gsm). Furthermore, an assembly of single-layered fabrics gave significantly improved times to reach this same level and was significantly longer than a single-layered fabric having the same total area density; this demonstrated the importance of entrapped air between adjacent layers in a garment assembly.

One early authoritative study of the thermal insulative properties of fabrics was that by Perkins (1979) who studied a large number of fabrics with an area density range of 85–740 gsm as single layers. He selected an incident radiant source intensity of up to 16.8 kW/m^2 and a convective flame source of 84 kW/m^2, which is considered to be commensurate with the exposure typically experienced by firefighters. Behind each fabric was a heat flux meter which enabled time versus heat flux to be determined. Using a standard burn-injury curve that relates delivered heat to incipient second-degree burn threshold level (Derksen *et al.*, 1961), performance of fabrics could be measured in terms of time to reach the latter. Their results may be summarised as follows:

- For radiant heat fluxes of 8.4 kW/m^2, fabric area density determines protection efficiency with air permeability also influencing performance – open constructions enhance heat flow. Differences in fibre type have little effect.
- At heat fluxes of 12.6 and 16.8 kW/m^2, the fibre properties become important and char-forming fibres like FR cotton and FR wool become superior.
- Exposures to the convective flame at 84 kW/m^2, shows the FR wool fabrics to yield significantly higher times than FR cotton and aramid fabrics of similar weight.

An alternative method is to determine the so-called thermal protective performance index as described in the ASTM Test Method for Thermal Protective Performance (TPP) of Materials for Clothing by Open-flame Method (D 4108-82, -87 and subsequent revisions) where TPP for a fabric assembly is the burn threshold time multiplied by the incident heat flux. This method has been used by a number of authors (Shalev and Barker, 1986; Day 1988; Barker *et al.*, 1996). At the same time, Benisek *et al.* (1979) published their study of the insulative behaviour of a range of fabrics subjected to a convective flame with a temperature of 1,050 °C, heat transfer from a radiant panel according to BS 3791:1970 and hot molten metal. For heat transfer from radiant heat, the time for a copper disc located behind the fabric to rise by 25 °C is defined as the Thermal Protective Index or TPI and this gives a simple measure of fabric thermal protection against first-degree burns. Table 15.8 lists TPI values determined by Benisek *et al.* (1979), which although determined over a quarter of a century ago, do indicate the effectiveness of aluminisation. Here aluminised polyester films are less reflective than aluminium spray coatings which are very much less effective than a bonded aluminium film to the fabric surfaces. It is important, however, that such fabrics must be kept clean if they are to remain efficient.

Table 15.8 Thermal protective indices of selected fabrics (Benisek *et al.*, 1979)

Fabric	Construction	Area density, gsm	Thermal protective index, s
100% Zirpro wool	Twill	260	8.8
100% Zirpro wool/aluminised polyester film	Twill	378	32.7
100% Zirpro wool/aluminised by spraying	Twill	297	172
85% Zirpro wool/15% glass	Twill	300	13.5
85% Zirpro wool/15% glass/ aluminised polyester film	Twill	448	34.3
85% Zirpro wool/15% glass/aluminised by spraying	Twill	351	143
100% aramid/bonded aluminium film	Twill	339	401

Their effectiveness under convective flame conditions will be compromised by both smoke deposition and film oxidation (Shalev and Barker, 1983).

The now-obsolete test BS 3791 used to generate the data in Table 15.8 is the basis of the current standard for protective clothing BS EN ISO 6942:2002 where a radiant source temperature 1,070 ºC is used and times to achieve temperature rises behind a sample of 12 and 24 ºC are recorded at any chosen incident heat flux level, Q_o, from the following ranges: Low – 5 and 10 kW/m^2; Medium – 20 and 40 kW/m^2 and High – 80 kW/m^2. In parallel, transmitted heat flux density, Q_c, and the heat transmission factor, TF(Q_o), may be calculated for a given assembly. The radiant heat transfer index (RHTI) at a given incident heat flux intensity, Q_o, is defined as the mean time taken, t_{24}, for the temperature taken in the calorimeter at the rear of the assembly to rise by 24 ± 0.2 ºC.

BS EN 367 (see Table 15.6) defines the method for assessing convective heat transfer following exposure to a flame with a heat flux of 80 kW/m^2 and describes the means of calculating the heat transfer index or HTI which should not be confused with the TPI discussed above for radiant panel exposure or indeed, the TPP determined for a flame source according to ASTM D 4108-87 and subsequent revisions. The HTI, like RHTI above, is the mean time taken, t_{24}, for the calorimeter at the rear of the assembly away from the flame to rise by 24 ± 0.2 ºC. This same standard offers a banding of fabric assembly performances from 1 to 5 that cover the HTI limits of 3–6 s for Band 1 (single layer fabrics) to over 31 s for Band 5. Fabric assemblies in this last category will be very thick and be for special applications whereas Band 3 covers HTI values from 13 to 20s and spans the requirement for specialist firefighters' clothing of 16 s (see section 15.6.3).

Hot metal splash resistance is determined using BS EN 373:1993 and the challenges that different molten metals pose have been discussed in section 15.5.1 above, although setting standards for its determination and translation to actual performance are not simple (Proctor and Thompson, 1988). Work reported by Benisek and Edmondson (1981) assessed different metal splash-fabric combinations by determining the mass of a given metal required to damage a PVC skin-simulant film placed on the reverse of the fabric under test (Mehta and Willerton, 1977). Molten drops impinged upon upper fabric surfaces orientated at 45º to the horizontal so that droplets during impact had time to thermally degrade the fabric surface and either glance off or stick to and burrow into the fabric. In BS EN 373:1993, the underlying embossed PVC film (with an area density of 160 gsm) is designed to show loss of embossing and even small holes when exposed to excessive localised heat and hence exhibit damage commensurate to skin. In this test, shown in Fig. 15.2, 50 g molten metal (at about 50 ºC higher than its respective melting point) is dropped onto a supported fabric. If no PVC damage is apparent, the test is repeated with fresh fabric and PVC samples but with an increasing incremental mass of molten metal (10 g) until damage is apparent. Conversely, if 50 g molten metal damages the PVC, incrementally decreasing masses are used until no damage is apparent. The molten mass index for a given fabric is the average of four highest masses that do not give rise to PVC damage.

15.2 A fabric being tested to BS EN 373:1993 (courtesy of BTTG Fire Testing Laboratory, Altrincham, UK).

15.6.2 Integrated component and product testing

As textile materials like protective clothing are used in more complex and demanding environments, so the associated test procedures become more complex. While the BS EN tests outlined above and listed in Table 15.6 relate to testing individual fabrics, there is an increasing need to test the ability of the final garment and even clothing system to protect the wearer during a defined thermal or fire environment. One of the first uses of a simulated human figure or manikin was reported by Finley and Carter in 1971 and in this work garments were ignited by a bunsen burner. Subsequently, the Du Pont 'Thermoman' (Chouinard *et al.*, 1973) provided the first attempt at recording the temperature profile and simulated burn damage sustained by the torso when clothed in defined garments (usually prototype protective garments) during exposure to an intense fire source. This latter is typically a series of gas burners yielding a heat flux of 80 kW m^{-2} that impinge on the front and rear of the clothed manikin.

The use of manikins has increased since this time and reviews of their use have been compiled by Krasny (1982) and Norton *et al.* (1985). Over ten years ago Sorensen (1992) reviewed attempts to establish this and related manikin methods as a standard method and subsequently draft standard procedures have been produced (e.g. ISO/DIS 13506). While not a mandatory test, it is often specified by fire service purchasing authorities in order to select clothing systems and is now offered as an optional test in the internationally accepted standard for firefighters' clothing, BS EN ISO 469 (see Table 15.6). A major challenge with such a test is determining its sensitivity to garment fit since overly loose garments will enable flames to penetrate between overlapping layers (e.g. between jacket and trousers) and too tight a fit will reduce the thickness of underlying air layers. Furthermore, while testing the ability of a given clothing system to protect a wearer from receiving torso burns measured at first-, second- and third-degree levels, it also ignores the consequences of the effect of heat and flame on the exposed head of the wearer. Furthermore, it does not enable the heat fatigue experienced by wearers to be measured during use of garments that can 'pass' the test. However, since full-scale manikin tests offer a more realistic means of testing full clothing assemblies they continue to draw research interest (Bajaj, 2000). Notable among these more recent studies is the work of Crown, Dale and coworkers at the University of Alberta who have used an instrumented manikin to test garment performance in flash fires (Crown and Dale, 1993).More recent work by this group includes a comparison of results from bench scale test-derived data such as TPP with manikin results expressed as percentage of body suffering defined burn levels (Crown *et al.*, 2002). The reader is referred to Chapter 9 for a more detailed evaluation of manikins in general.

15.6.3 Composite standards: firefighters' clothing*

In Table 15.6 are a number of composite standards which offer a series of tests for specific working or hazard environments such as clothing for welders (BS EN 470:1995) and workers exposed to heat (BS EN 531:1995). In addition, they exist for protective gloves (BS EN 420) and not least, for firefighters' clothing (BS EN 469:1995). These standards may be examined in more detail by direct reference to them and in summary form by referring to the review by Bajaj (2000). However, in order to illustrate their character and structure, it is worth examining BS EN 469:1995 for firefighters' clothing in greater detail. As part of the European Union Personal Protective Equipment Directive, the standard BS EN 469:1995 is an attempt to create a single, normalised standard method applicable to firefighters' clothing throughout the EU. Such a standard may be

---

* See also Chapter 22.

applied to any part of the full garment assembly from the outershell jacket and overtrousers (or a single outer coverall) to the underlying outer and underwear garments. Gloves and hoods are covered by other standards listed in Table 15.6. There are in the order of 2 million firefighters including part-time personnel in the EU and so not only is the market for clothing considerable, but use of a standard test should ensure that each member state is providing the same minimal levels of protection to its firefighting workforce. However BS EN ISO 469 is a composite test in which a portfolio of test methods and performance requirements are defined as shown in Table 15.9.

The performance specifications specifically relating to thermal protection include ignition and flame spread (BS EN 532) and heat transfer to radiant (BS EN ISO 6942) and convective (BS EN 367) heat. For instance, the radiant heat transfer index, RTHI, values for a multilayer assembly (to BS EN ISO 6942 Method B) at 40 kW/m^2 should be $\geq$ 13 s and the RTI values for flame exposure (80 kW/m^2), $\geq$ 22 s. In addition are tests relevant to the overall performance of

Table 15.9 Test methods within the composite standard for firefighters' clothing, BS EN 469:1995

Property tested	Standard	Principal performance specifications
Flame spread	BS EN ISO 15025:2002 (replaces BS EN 532:1995 and BS 5438)	No flame extending to top or edge, no hole formation and afterflaming and afterglow times $\leq$ 2 s
Heat transfer (flame)	BS EN 367:1992 (ISO 9151)	$HTI_{24} \geq 13$ s
Heat transfer (radiant)	BS EN ISO 6942:2002 at 40 kW/m^2	$RHTI_{24} \geq 22$ s
Residual strength	ISO 5081 after BS EN ISO 6942 Method A at 10 kW/m^2	Tensile strength $\geq$ 450 N
Heat resistance	BS EN 469:1995 Annex A	No melting, dripping or ignition
Tensile strength	ISO 5081	Tensile strength $\geq$ 450 N
Tear strength	ISO 4674/A2	Tear strength $\geq$ 25 N
Surface wetting	BS EN 24920:1992 (ISO 4920:1981)	Spray rating $\geq$ 4
Dimensional change	ISO 5077	$\leq$ 3%
Penetration by liquid chemicals	BS EN 368:1993 (for 40% NaOH, 36% HCl and 36% H_2SO_4 at 20°C)	$\leq$ 80% run off
Water resistance	BS EN 20811:1992 (ISO 811:1981)	Defined by manufacturer/ customer
Breathability	BS EN 31092:1994 (ISO 11092:1993)	Defined by manufacturer/ customer
Contact heat transfer	BS EN 702:1995 (ISO 12127)	Defined by manufacturer/ customer
Manikin (optional)	ISO/DIS 12127	Defined by manufacturer/ customer

15.3 The BTTG RALPH burner flames at 80 kWm^{-2} heat flux engulfing the instrumented manikin (courtesy of BTTG Fire Laboratory, Altrincham, UK).

firefighters' clothing, including tensile and tear strength, surface wettability and others. Again the reader is referred to the main standard and its component parts for full details of each test. Of interest is the optional inclusion of the manikin test ISO/DIS 13506 mentioned above in Section 15.5.2. In this, the manikin is that developed at British Textile Technology Group in the UK using the RALPH II (Research Aim Longer Protection Against Heat) manikin (Sorensen, 1992; Bajaj, 2000) in which a clothed manikin is subjected to a full flame exposure with gas burner flames of about 800 ºC and heat flux, 80 kW/m^2 for an 8 s application time. The torso is instrumented to determine those areas which will suffer first- and second-degree burns and a map of burnt areas is produced along with respective percentage of body area burn values. Figure 15.3 shows the intensity of the impinging flames in the BTTG RALPH manikin; note that the whole torso is engulfed within the flames and only the boots are observable.

15.7 Future trends

With the recent normalisation of test methods across the EU and the generation of the individual and composite standards discussed above in section 15.6, it is probable that very little change in standard testing methodology will occur in the near future. The development of instrumented manikins and their acceptance as an optional test (e.g. ISO/DIS 13506) perhaps points the way toward their greater use on the one hand and their more general adoption for a wider range of thermally protective clothing performance requirements on the other. At the time of writing, EN 469:1995 is currently being updated and this optional test will be included as a new annex (Annex E). In addition, the heat and flame performance criteria defined in Table 15.9 are being modified to allow for differing levels of performance, level I being less than the present requirements and level II being similar. Thus the convective or flame heat performance criterion in Table 15.9 of a heat transfer index, $HTI_{24} \geq 13$ s will be replaced by two levels – level I with $HTI_{24} \geq 9$ s and level II with $HTI_{24} \geq 13$ s. Similarly the radiant heat transfer index values that define radiant heat performance will change from $RHTI_{24} \geq 22$ s to $RHTI_{24} \geq 10$ s for level I and to $RHTI_{24} \geq 22$ s for level II performance. Alongside these changes are the proposed requirement (instead of being optional in the present 1995 version) of comfort performance criteria in terms of quantifiable moisture transfer and ergonomic parameters.

While heat fatigue is about to be recognised in the proposed revision of EN 469, it will still remain a challenge associated with such clothing assemblies, and the next generation of instrumented manikins may include sensors that enable prediction of its onset and magnitude. This would be more likely to be the case, however, if a ‘working manikin’ could be developed for assessing fire resistance as well as comfort and eventual onset of heat fatigue by a typical wearer working in a typical fire or other thermally hazardous environment. While the published literature gives little detailed information regarding specific developments of thermal and fire protective clothing that fit within the ‘smart’ or ‘sensored’ textile fields, the concepts have been discussed by a number of authors (Gries (2003), Tao X (2002)) and indications of developments reported (Vogel (2002), Anon (2003), Butler (2003)).

With regard to possible new materials, it is doubtful whether any really new generic fibre groups exhibiting unusual thermal characteristics will appear in the next decade. This is because, as section 15.3 has shown, the thermal protective clothing designer has a fair range of fibres, with or without after-treatments, to choose from and which enable a balance of performance for a specific application and cost to be achieved. However, because of the need for protective textiles and garments to be more multifunctional and reactive to defined thermal threats, the next generation may also be required to determine the degree of a given threat and respond appropriately. This, of course, brings us into the realms of so-called ‘smart’ textiles as mentioned above in which both the use of embedded sensors and the means of increasing levels of protection within a given textile structure may be anticipated. At the moment, however, the development of such textiles is an aspiration that should provide direction for the present and future generation of thermally protective textiles.

15.8 References

Anon (2003), 'Uniforms of the future', *Textile Horizons,* July/August, 7.

Bajaj P (2000), 'Heat and flame protection', in *Handbook of Technical Textiles,* Horrocks A R and Anand S A (editors), Cambridge, Woodhead Publishing, pp 223–263.

Baitinger W F (1979), 'Product engineering of safety apparel fabrics: insulation characteristics of fire retardant cottons', *Text. Res. J.,* 49, 221.

Barker R and Brewster E P (1982), 'Evaluating the flammability and thermal shrinkage of some protective fabrics,' *J. Ind. Fabrics,* 1 (1), 7–17.

Barker R L and Coletta G C (1986), *Performance of Protective Clothing,* ASTM Special Technical Publication 900, Philadelphia, ASTM, Philadelphia.

Barker R and Yener M (1981), 'Evaluating the resistance of some protective fabrics to molten iron', *Text. Res. J.*, 51, 533.

Barker R, Geshury A J and Behnke W P (1996), 'The effect of Nomex®/Kevlar® fibre blend ratio and fabric weight on fabric performance in static and dynamic TPP tests', in *Performance of Protective Clothing, Fifth Volume,* Johnson S and Mansdorf S Z (eds), ASTM Special Technical Publication 1237, West Conshohocken, USA, ASTM.

Beck P P, Gordon P G and Ingham P E (1976), 'Thermogravimetric analysis of flame-retardant-treated wools', *Text. Res. J.,* 46, 478.

Benisek L (1971), 'Use of titanium complexes to improve the natural flame retardancy of wool', *J. Soc. Dyers. Col.,* 87, 277–278.

Benisek L (1981), 'Antagonisms and flame retardancy', *Text. Res. J.,* 51, 369.

Benisek L and Edmondson G K (1981), 'Protective clothing fabrics . Part I Against molten metal hazards', *Text. Res. J.,* 51, 182.

Benisek L and Phillips W A (1981), 'Protective clothing fabrics. Part II Against convective heat (open-flame) hazards', *Text. Res. J.,* 51, 191–196.

Benisek L, Edmondson G K and Phillips W A (1979), 'Protective clothing – evaluation of wool and other fabrics', *Text. Res. J.,* 49, 212–225.

Buszard D (2004), 'The present European position: textile flame retardants and risk assessment', in proceedings of the conference, *Ecotextile04*, *The Way Forward for Sustainable Development in Textiles*', 7-8 July 2004, Bolton, UK.

Butler N (2003), 'How to succeed in developing safety and protective fabrics', *Technical Textiles International,* 12(3), 23–26.

Chouinard M P, Knodel D C and Arnold H W (1973), 'Heat transfer from flammable fabrics', *Text.Res.J.,* 43, 166–175.

Consumer Protection Act (1987), the Furniture and Furnishings (Fire) (Safety) Regulations, 1988, SI1324 (1988), London, HMSO, 1988.

Crown E M and Dale J D (1993), 'Built for the hot seat', *Canadian Textile J.,*Mar., 16–19.

Crown E M, Dale J D and Bitner E (2002), 'A comparative analysis of protocols for measuring heat transmission through flame resistant materials: capturing the effects of thermal shrinkage', *Fire Mater.,* 26 (4–5), 207–214.

Dawn F S and Morton G P (1979), 'Cotton protective apparel in the Space Shuttle', *Text.*

Res. J., 49, 197–201.

Day M (1988), 'A comparative evaluation of test methods and materials for thermal protective performance', in *Performance of Protective Clothing, Volume 2,* Mansdorf S Z, Sager R and Neilsen A (editors), ASTM Special Technical Publication 989, Philadelphia, ASTM, pp 108–120.

Day M and Sturgeon P Z (1987), 'Thermal radiative protection of firefighters' protective clothing', *Fire Technol.,* 23 (1), 49–59.

Derksen W L, Monahan T I and DeLhery G P (1961), 'The temperatures associated with radiant energy skin burns', in *Temperature – Its Measurement and Control in Science and Industry, Vol.3, Part 3*, New York, Reinhold, pp 171–175.

Dombrowksi R (1996), 'Flame retardants for textile coatings', *J. Coated Fabrics*, 25, 224.

Eaton P (2000), 'Flame retardancy test methods for textiles', *Rev. Prog. Colouration,* 30, 51–62.

Finley E L and Carter W H (1971), 'Temperature and heat flux measurements on life-size garments ignited by flame contact', *J. Fire Flammability,* 2, 298–319.

Flambard X, Bourbigot S and Poutch F (2005), 'Fire reaction of seats: the wool/para-aramid blend', *Textiles & Usages Techniques*, 56, 23–25.

Gries T (2003), 'Smart textiles for technical applications', *Technische Textilien*, 46(2), E66.

Hall M E and Shah S (1991), 'The reaction of wool with N-hydroxymethyl dimethylphosphonopropionamide', *Polym. Degrad. Stab.,* 33, 207.

Hearle J W S (2001), *High Performance Fibres,* Cambridge, Woodhead Publishing.

Holme I (2003), 'Water repellency and waterproofing', in *Textile Finishing,* Heywood D (editor), Bradford, Society of Dyers and Colourists, pp 135–213.

Holmér, I (1988), 'Thermal properties of protective clothing and prediction of physiological strain', in *Performance of Protective Clothing, Volume 2,* Mansdorf S Z, Sager R and Neilsen A (eds), ASTM Special Technical Publication 989, Philadelphia, ASTM.

Holmes D A (2000), 'Waterproof breathable fabrics', in *Handbook of Technical Textiles,* Horrocks A R and Anand S A (editors), Cambridge, Woodhead Publishing, pp 282–315.

Horrocks A R (1986), 'Flame retardant finishing of textiles', *Prog. Rev. Colouration*, 16, 62–101.

Horrocks A R (1996), 'Developments in flame retardants for heat and fire resistant textiles – the role of char formation and intumescence', *Poly.Degrad. Stab.,* 54, 143–154.

Horrocks A R (2001), 'Textiles', in *Fire Retardant Materials,* Horrocks A R and Price D (eds), *Fire Retardant Materials,* Cambridge, Woodhead Publishing, pp 128–181.

Horrocks A R (2003), 'Flame retardant finishes and finishing', in *Textile Finishing,* Heywood D (ed.), Bradford, Society of Dyers and Colourists, 2003, pp 214–250.

Horrocks A R and Davies P J (2000), 'Char formation in flame-retarded wool fibres; Part 1 Effect of intumescents on thermogravimetric behaviour', *Fire Mater.,* 24, 151–157.

Horrocks A R and Price D (2001), *Fire Retardant Materials,* Cambridge, Woodhead Publishing.

Horrocks A R, Price D and Tunc M (1987), 'The burning behaviour of textiles and its assessment by oxygen index measurements', *Text. Prog.,* 18 (1-3), 1–205.

Horrocks A R, Eichhorn H, Schwaenke H, Saville N and Thomas C (2001), 'Thermally resistant fibres', in Hearle J W S, *High Performance Fibres,* Cambridge, Woodhead Publishing, pp 289–324.

Horrocks A R, Kandola B K, Davies P J, Zhang S and Padbury S A (2005), 'Developments in flame retardant textiles', *Polym. Degrad. Stab.*, 88, 3–12.

Johnson S and Mansdorf S Z (1996), *Performance of Protective Clothing, Fifth Volume,* ASTM Special Technical Publication 1237, West Conshohocken, USA, ASTM.

Krasny J (1982), 'Flammability evaluation methods for textiles', in *Flame Retardant Polymeric Materials, Volume 3,* Lewin M, Atlas S M and Pearce E M, (eds), New York, Plenum, pp 155–200.

Krasny J (1986), 'Some characteristics of fabrics for heat protective garments', in Barker R L and Coletta G C (eds), *Performance of Protective Clothing,* ASTM Special Technical Publication 900, Philadelphia, ASTM, pp 463–474.

Lee Y M and Barker R (1987), 'Thermal protective performance of heat-resistance fabrics in various high intensity heat exposures', *Text. Res. J.,* 57, 123.

Lewin M and Mark H F (1997), 'Flame retarding of polymers with sulfamates; Part 1 Sulfation of cotton and wool,' 8th annual conf *Recent Advances in Flame Retardancy of Polymer Materials*, Stamford, USA, Business Communications Company.

Mansdorf S Z, Sager R and Neilsen A (1988), *Performance of Protective Clothing, Volume 2,* ASTM Special Technical Publication 989, Philadelphia, ASTM.

Mehta P N and Willerton K (1977), 'Evaluation of clothing materials for protection against molten metal', *Text. Inst. Ind.,* 15, 334–337.

Norton R J, Kandolph S J, Johnson R F and Jordon K A (1985), 'Design, construction and use of Minnesota Woman, a thermally instrumented mannequin', *Text. Res. J.,* 55, 5–12.

Perepelkin K E (2001), 'Chemical fibers with specific properties for industrial application and personnel protection', *J. Ind. Text.,* 31 (2), 87–102.

Perkins R M (1979), 'Insulative values of single-layer fabrics for thermal protective clothing', *Text. Res. J.,* 49, 202–212.

Proctor T D and Thompson H (1988), 'Setting standards for the resistance of clothing to molten metal splashes', in *Performance of Protective Clothing, Volume 2,* Mansdorf S Z, Sager R and Neilsen A (editors), ASTM Special Technical Publication 989, Philadelphia, ASTM.

Raheel M (1994), 'Chemical protective clothing', in Raheel M (ed.), *Protective Clothing Systems and Materials,* New York, Marcel Dekker, pp 39–77.

Raheel M, Perenich T A and Kim C (1994), 'Heat- and fire-resistant fibers for protective clothing', in Raheel M (ed.), *Protective Clothing Systems and Materials,* New York, Marcel Dekker, pp 197–224.

Rebenfeld L, Miller B and Martin J R (1979), 'The thermal and flammability behaviour of textile materials', in *Applied Fibre Science, Vol 2,* ed. F Happey, London, Acad. Press, p 465.

Scott R A (2000), 'Textiles in defence', in *Handbook of Technical Textiles,* Horrocks A R and Anand S A (editors), Cambridge, Woodhead Publishing, pp 425–460.

Shalev I and Barker R (1983), 'Analysis of heat transfer characteristics of fabrics in an open flame exposure', *Text. Res. J.,* 53, 475.

Shalev I and Barker R (1986), 'Predicting the thermal protective performance of heat-protective fabrics from basic properties', in *Performance of Protective Clothing,* Barker R L and Coletta G C (eds), ASTM Special Technical Publication 900, Philadelphia, ASTM, Philadelphia, pp 358–375.

Shirley Institute (1982), *Protective Clothing,* Shirley Publication S45, Shirley Institute, Manchester.

Sorensen N (1992), 'A manikin for realistic testing of heat and flame protective clothing', *Technical Text. Int.*, 8–12.

Stull J O and Schwope A D (1997), *Performance of Protective Clothing, 6th Volume,* ASTM Special Technical Publication 1273, Philadelphia, ASTM.

Tao X (2002), 'Sensors in garments', *Textile Asia,* 33(10), 38–41.

Tolbert T W, Dugan J S, Jaco P and Hendrix J E, Springs Industries (1989), Fire Barrier Fabrics, US Patent Office, 333174, 4 April.

Troitzsch J (2004), *Plastics Flammability Handbook*, 3rd edn*,* Munich, Hanser.

Valentin N (2004), 'Thermal testing of firemen's clothing', *Textiles à Usage Techniques (TUT),* 3(53), 51–53.

Vigo T L (1994), 'Protective clothing effective against biohazards', in Raheel M (ed.), *Protective Clothing Systems and Materials,* New York, Marcel Dekker, pp 225–244.

Vogel C (2002), 'Firefighter turnout gear with integrated sensors', *Textiles a Usage Techniques*, 46, 38–41.

Vosburgh J (1960), 'The heat treatment of Orlon acrylic fibre to render it fireproof', *Text. Res J.*, 30, 882.

Weil E D and Levchik S V (2004), 'Commercial flame retardancy of thermoplastic polyesters. A review', *J. Fire Sci.,* 22(4), 339–350.

Woodruff F A (2003), 'Coating, laminating, bonding, flocking and prepregging', in *Textile Finishing,* Heywood D (ed.), Bradford, Society of Dyers and Colourists, pp 447–523.

15.8.1 Selected web-sites active at the time of publishing

Exemplar manufacturers of protective textiles

http://www.heathcoat.co.uk/military_products.htm
http://www.baltex.co.uk/
http://www.firegard.co.uk/SAFETY/Clothing/clothing.html
www.bristol-uniforms.com
www.bennettsafetywear.co.uk

Fibre producers

http://www.kermel.com/
http://www.toyobo.co.jp/e/seihin/kc/pbo/
http://www.teijin.co.jp/english/about/enterprise/index.html
http://www.roehm.de/en/performanceplastics?content=/en/performanceplastics/inspec.html
http://www.ibena.de/protect/english/Protective_fabric/Welding/welding.html
http://www.lenzing.com/lenzred/frameset.jsp
http://www1.dupont.com
http://www.personalprotection.dupont.com/
http://www.dupont.com/nomex/europe/protectiveapparel/index.html
http://www.pbigold.com/
http://www.celanese.com/index/about_index/innov-home/innovation-product-innovation/innov-prod/innov-pbi.htm
http://www.sglcarbon.com/sgl_t/fibers/panox.html

Civilian protection and protection of industrial workers from chemicals

1 Introduction

The evaluation of chemical protective clothing (CPC) designs, design features, performance, and applications requires an understanding of the types of chemical protective clothing available for protection. The types of chemical protective clothing available in the marketplace and thus the choices available to the end user have changed dramatically over the past two decades and continue to increase in diversity. Chemical protective clothing exists in a variety of designs, materials, and methods of construction, each having advantages and disadvantages for specific protection applications. End users should have an understanding of the different types of chemical protective clothing and their features in order to make appropriate selections. It is important to realize that chemical protective clothing that appears to be similarly designed may offer significantly different levels of performance. Thus chemical protective clothing performance must be carefully scrutinized in addition to design and features. Furthermore, CPC must be properly sized to provide adequate protection. Improperly sized or ill-fitting chemical protective clothing may reduce or eliminate protective qualities of CPC.

Chemical protective clothing can be selected properly only when performance data indicate that resistance to chemicals lasts for the duration of anticipated, worst-case exposures. Relating chemical performance directly with possible exposures mandates a need for rigorously tested protective clothing. This clothing must also demonstrate acceptable integrity for overall protection and provide sufficient strength, durability, and physical hazard resistance. In addition, chemical protective clothing must be functional allowing the wearer to safely perform the required tasks at an acceptable level of comfort.

2 Classification of chemical protective clothing

Chemical protective clothing may be classified by its design, performance, and intended service life. These three characteristics of chemical protective clothing will permit the end user to understand the type of CPC item being considered or used, as well as indicate its potential limitations.[1] The following sections describe how CPC can be ‘type’ classified in these three ways.1

Classification by design

Classification of CPC by its design usually reflects how the item is configured or the part of the body area or body systems that it protects. For example, a hood by design provides protection to the wearer’s head. While there are a variety of different forms of clothing and equipment that are used for protection from industrial chemicals, the discussion in this chapter is limited to various types of textile-based full body or partial body garments. Gloves, footwear, and face/eye protection are not covered, though many of the same principles apply to these items. Table 12.1 shows the different CPC designs associated with different areas of body protection.

Classification of chemical protective clothing by design may also provide an indication of specific design features that differentiate CPC items of the same type. For example, totally encapsulating chemical protective suits are configured with significant design differences when compared to splash suits. Some designs of chemical protective clothing may offer varying protection against hazards in different parts of the CPC item. For example, the use of coated textile materials in the front portion of an apron may offer liquid chemical protection to wearer’s

Table 12.1 Chemical protective clothing design types by body area

Body area(s)	Type
Entire body	Totally encapsulating suit 2-piece suit (hooded jacket with visor with pants or overalls)
Torso, head, arms, and legs (excluding hands, feet, and face)	Hooded coveralls 2-piece ‘splash’ suit (hooded jacket and pants or overalls)
Torso, arms and legs	Coveralls 2-piece ‘splash’ suit (jacket and pants or overalls) Smock
Top torso and arms	Coat or jacket Lab coat
Bottom torso and legs	Pants
Torso (front) and arms	Sleeved apron
Torso (front)	Apron
Head and face	Hood with visor
Head	Hood
Foot	Booties Boot or shoe covers

front torso, but non-coated textile portions of the same clothing may offer no protection from chemicals. Therefore, it is important to realize that even apparent CPC coverage of a specific body area, in and of itself, does not guarantee protection of that body area.

A further means of distinguishing chemical protective clothing by design is to indicate the materials used in the CPC construction. Materials will possess different characteristics that impact both the performance and wearability of the CPC item. For example, rubber coated textiles behave much differently than plastic laminates. Owing to their elasticity, rubber materials are more likely to offer form fitting designs but may weigh more than comparable plastic laminates, which tend to offer better chemical resistance. Since material choices vary with the type of item, a more detailed discussion is provided in the respective section on the availability and characteristics of respective materials for different types of chemical protective clothing.

12.2.2 Classification by performance

Classification of chemical protective clothing by performance indicates the actual level of performance to be provided by the item of CPC. This may include a general area of performance or a more specific area of performance. For example, while two items of CPC might be considered to be chemical protective clothing, one item may provide an effective barrier to liquids but not to vapors, while the other item provides an effective barrier to both liquids and vapors. Classification of CPC by performance is best demonstrated by actual testing or evaluations of the chemical protective clothing with a standard test that relates to the type of desired protection (see sections 12.4 through 12.6). These tests can then be used as demonstrations of protection against the anticipated hazards and often become the basis of claims by the manufacturer for their products. However, intended or manufacturer-claimed performance does not always match actual performance. Furthermore, performance claims should be uniformly applied to all parts of the CPC item, i.e., the seam should offer the same performance as the material, otherwise the performance classification should be limited by the weakest element of the CPC design. The specific classification of chemical protective clothing will be related to the types of protection offered against chemical hazards. Table 12.2 describes a hierarchy of chemical barrier performance.

In general, chemical protective clothing that protects against gases and vapors, will also protect against liquids and particulates, and CPC effective against liquids will also prevent penetration of particulates. However, there are exceptions. For example, some chemical protective clothing based on adsorptive materials (such as those using air-purifying respirator cartridges) may prevent penetration of gases and chemical vapors, but not when exposed to liquids if the CPC is splashed by or immersed in liquid chemical. Other performance features

Table 12.2 Hierarchy of chemical barrier performance

Type of chemical barrier	Protection offered*
Permeation-resistant	Prevents or limits any contact with chemicals in the form of gases/vapors, liquids, or particulates (solid)
Vapor penetration-resistant	Prevents wearer contact with atmospheric vapors or gases
Liquid penetration-resistant**	Prevents wearer contact with liquids
Particulate penetration-resistant	Prevents wearer contact with particles

* Protection offered is specific to chemical or chemical characteristics.
** Liquid penetration resistance is sometimes subdivided into two categories where chemical protective clothing may be resistant to liquid penetration under pressure as might be associated with spraying liquid (e.g., from a burst pipe) versus CPC that may limit penetration under conditions of a light splash or mist.

may be related to the non-chemical hazards in the workplace, the durability of the CPC in different use environments, or the impact of the CPC on the wearer. The respective performance of CPC against these properties can similarly be ranked or rated, but may create tradeoffs between desired characteristics.

12.2.3 Classification by service life

The classification of chemical protective clothing by expected service life is based on the useful life of the CPC item. Thus, service life reflects the longevity of the product and how it relates to the user's expectations. The service life of chemical protective clothing generally fits into three classes:

- Disposable after a single use – CPC products that are relatively inexpensive, which cannot be adequately, cleaned, reserviced, or maintained after use, or it is easier to dispose of and replace the CPC rather than provide care or maintenance.
- Limited use – CPC where some cleaning, care, and maintenance is possible, but the CPC may not be reusable under rigorous physical conditions, or CPC is eventually degraded by use and maintenance processes.
- Reusable – CPC that can be readily cleaned and maintained, and still continue to provide acceptable performance.

Unfortunately, chemical protective clothing manufacturers do not always specify the service life of their products and may also not indicate conditions for retiring of CPC. Some chemical protective clothing may also have limited 'shelf life' (i.e., time in storage before use) because of material degradation that can take place in storage due to heat, ozone, or material self-degradation. Of course any item of chemical protective clothing can be rendered unusable if irreversibly contaminated or damaged in use.

Chemical protective clothing service life is a function of three factors:

1. Durability – how CPC maintains its performance with use.
2. Ease of serviceability – the user's ability to care for, maintain, and repair CPC so that it remains functional for further use.
3. Life cycle cost – the total costs for purchase, using, and maintaining an item of CPC.

Durability

Chemical protective clothing durability is demonstrated by the length of time that the CPC item provides acceptable performance given the range of use conditions, care, and maintenance. Unacceptable performance may be evident through physical changes in the chemical protective clothing item such as:

- rips, tears, or separation of materials and seams
- thin spots or cracks in coated materials or protruding fibers
- unexplained material discoloration
- diminished functionality of CPC component parts

Unacceptable performance may also not be readily evident unless products are carefully examined by product manufacturers or subject to destructive testing.[2] Estimates of product durability can be made through product testing for simulating product wear but most often are derived from field experience involving actual product use. Some products are expected to lose some performance in certain property areas; the acceptability of any drops in performance related to protection must be examined by the end user.

Ease of re-servicing

Some types of chemical protective clothing can be serviced or repaired to extend service life. This servicing and repair is considered part of a regular care and maintenance program to allow CPC to meet its expected service life. For example, NASA has an elaborate capability for cleaning, decontaminating, repairing, and testing propellent handlers' ensembles used for protecting launch site personnel during hypergolic fuel operations.[3] Other types of chemical protective clothing may not be easily repaired or cannot be repaired without manufacturer or special assistance.

The most significant aspect of reservicing chemical protective clothing is the ease of decontamination. This is an important issue because the end user must have some confidence that the CPC item is contamination free. One of the reasons for the increasing popularity of disposable clothing is because its use obviates the difficult decision of determining if the clothing is clean enough for reuse. However, in many work environments, the levels of contamination may be low or the type of contamination may be readily removed by standard decontamination practices. Otherwise, destructive testing of clothing may be needed to determine if chemical contaminants have been adequately removed by the selected decontamination process.[4] If an item of CPC cannot be reserviced to bring it to an acceptable level of performance, then it cannot be reused. In addition, if the costs to repair or maintain the chemical protective item represent a significant proportion of the item's original cost, then the CPC item will probably not be reused.

Life-cycle cost

The life-cycle of chemical protective clothing includes all aspects of its selection, use, care, and maintenance until its ultimate disposal. Therefore, the life-cycle cost of chemical protective clothing is the sum of all costs for associated with an item of CPC. To compare different products on the same basis, life-cycle cost is usually represented as the cost per use for a CPC item.

The following costs should be considered in determining the life-cycle cost:

- purchase cost
- labor cost for selection/procurement of CPC
- labor cost for inspecting CPC
- labor and facility costs for storing CPC
- labor and materials costs for cleaning, decontaminating, maintaining, and repairing CPC
- labor and fees for retirement and disposal of used CPC.

The total life-cycle cost is determined by adding the separate costs involved in the chemical protective clothing life cycle and dividing by the number of CPC items and number of uses per item. A detailed method for estimating chemical protective clothing life-cycle cost is provided by Schwope and Renard.[5]

12.2.4 Overall type classification of chemical protective clothing

The overall representation of chemical protective clothing should be made with respect to the three classification systems:

- Design classification is needed to establish which parts of the body will be protected.
- Performance classification will indicate the type of protection that will be offered by the CPC.
- Service life classification will establish the expected longevity of the CPC.

The following specific example illustrates the application of this type classification approach. The chemical protective clothing item pictured in Figure 12.1 is a hooded coverall constructed of a coated non-woven material that provides liquid

12.1 Example of a disposal coverall providing full-body protection against liquid splashes.

splash protection to the wearer's torso, arms, legs, and head (excluding the face). The coverall is considered disposable because the material has low durability, cannot be easily decontaminated if splashed and has a relatively low cost for a single use. If this CPC item is combined with gloves, boots, and full facepiece respirator, then protection is afforded to the wearer's hands, feet, and face. However, the interfaces between the clothing items (e.g., garment sleeve end to glove) and the integrity of clothing seams and closure will affect the level of overall performance of the ensemble.

12.3 Garment types, materials, design features and sizing

Further understanding the type classification of chemical protective clothing requires examining the specific designs, design features, materials, and other attributes associated with specific CPC garments.

12.3.1 Garment material types

Protection of the body from chemicals may be provided from either full-body garments or partial body garments. Full-body garments are designed to provide protection to the wearer's upper and lower torso, arms, and legs. Full-body garments may also provide protection to the wearer's hands, feet, and head when auxiliary CPC is integrated with the garment to form a suit. Full-body garments may be single or multi-piece clothing items. Partial body garments provide protection to only a limited area of the wearer's body including the upper torso, lower torso, arms, legs, neck, or head. Table 12.3 indicates some of the characteristics and features associated with each of these types of chemical protective garments. The extent of body protection varies with the garment design. Many garment designs do not provide uniform protection for all areas of the body covered by the garment. The specific materials and design features associated with the garment design will also influence protection.

12.3.2 Garment materials

Materials used in chemical protective clothing include seven basic types:

1. textiles
2. unsupported rubber or plastics
3. microporous film fabrics
4. adsorbent-based fabrics
5. coated fabrics
6. plastic laminates
7. combination or specialized materials.

Table 12.4 provides some characteristics and examples of these materials.

Textile materials

Ordinary textile materials are generally not considered suitable for protection against chemicals, however special non-coated textile materials are used for a variety of applications involving particulates and light liquid spray from relatively non-hazardous chemicals. Though woven textiles are not often found in chemical protective clothing, very tightly woven, repellent-treated fabrics can provide some very low minimum protection against liquid exposure.[6] More common are nonwoven fabrics that have demonstrated barrier performance against particles and repellency of liquids. Two predominant examples of nonwoven fabrics are flashspun polyethylene (Tyvek®) and spunbond/ meltbown/ spunbond (SMS) polypropylene (Kleenguard®). These textiles are used because of their relatively low cost and because the materials provide a structure of microfibers that filter out dry particulates and many water-based liquids.

Table 12.3 Design characteristics and features associated with chemical protective garments

General garment type	Specific garment type	Characteristics and features
Full-body garments	Full-body suits	• One-piece garments which may offer a variety of entry options depending on the type and placement of the closure • Generally known as totally encapsulating suits, that encapsulate the wearer and other protective equipment such as the respirator (some designs may permit a respirator facepiece to integrate with a suit hood) • Includes other CPC attached to the suit such as gloves and footwear
	Jacket and pants combinations	• Mimic normal wearing apparel • Head protection provided by hood, usually without a visor • Generally provide some overlap of the waist portion of trousers with or without a collar, hood, or wrist protection • Generally use front closure • Pants usually rely on a zipper, snaps, or other front fly closure or drawstring/elastic waist • May have openings with closures at the foot end to allow entry while wearing footwear
	Jacket and overall combinations	• Similar to jacket and pants combination • Distinguished by a higher 'bib' style pants (overalls) that permits a shorter jacket • Some jacket combinations designed as pullover with hood • Overalls often use straps or gusset with snaps for adjusting garment on lower torso • Bib overalls usually provided with suspenders
	Coveralls	• One-piece garments, usually with a front closure, and have options for attachment of hoods, type of sleeve end (open or elastic), type of pant cuff end (open, elastic, or bootie)
Partial body garments	Hoods	• Cover the wearer's head and include either a face/eye opening or may be provided with an integrated faceshield or visor • Usually pullover design • Length affects integration with upper torso garments • Type of visor and size may vary (if present) • Size and type of face opening accommodates respirator or eye/face protection • Face opening closure options (elastic, pliable/stretchable material, drawstrings, ties, snaps, or hook and loop closures) • Bulk of the hood on the wearer's crown may affect the fit of helmets and respirator straps

Table 12.3 Continued

General garment type	Specific garment type	Characteristics and features
Partial body garments	Head covers and bouffants	• Provide protection to the wearer's upper head, but are most often used to contain or cover the wearer's hair • Bouffant style head covers are secured to the wearer's head by elastic around the periphery • Head covers may also be used as helmet covers as an aid to preventing contamination
	Aprons	• Consists simply of a flat piece of material contoured to the front of the body for providing lower or lower/upper torso protection • Lower part extends around the wearer's sides and ties in the back. • Aprons covering the upper torso are designated 'bib' aprons with a strap around the wearer's neck that holds up the 'bib' • Generally available in more than one size, designated by unisex rectangular dimensions, and are adjusted by the tie straps at the top or sides
	Lab coats	• Provide torso, arm, and upper leg protection • Of varying lengths and are generally offered in alphabetic sizing • Use front closures usually with snaps or buttons • May have open neck area or collar • Type and location of pockets are usually a design option
	Smocks	• Provide front torso, arm, and upper leg protection • Of varying lengths and are generally offered in alphabetic sizing • Use back closures with ties • May have open neck area or collar
	Shirts	• Provide protection to upper torso and arms (long-sleeved) • Mimic regular wearing apparel with differences in collar and type of closure
	Pants	• Provide protection to lower torso and legs • Mimic regular wearing apparel with differences in waist (fly or elastic)
	Sleeve protectors	• Provide protection from the wearer's hand to the shoulder area • Usually secured to the wearer's arm by several means or by elastic ends
	Chaps	• Partial pants which are open at the sides/back and are intended to provide wearer front leg protection (rarely used for chemical protection) • May incorporate belt or straps and may be flared at bottom to cover top of wearer's footwear
	Leggings	• Protect the wearer's lower leg (generally knee height) • Have elastic top or adjustable tops with snaps or tie closures • May have a flare for protecting the top of wearer's footwear

Table 12.4 Type of chemical protective garment materials

Material class	Characteristics	Examples	Type of protection
Textiles	Primarily nonwoven	Flashspun polyethylene (Tyvek) SMS Polypropylene (Kleenguard)	Dry particulate Light spray from water-based chemicals
Unsupported rubber or plastics	Thick rubber or plastic film	Polyvinyl chloride, PVC Chlorinated polyethylene, CPE (Chemturion)	Liquid splash, liquid or gas/vapor permeation
Microporous-film based	Polymer film with microscopic pores laminated to fabric	PTFE (Goretex) Polypropylene (NexGen, Kleenguard Ultra)	Liquid splash
Adsorbent-based	Material incorporating sorbent layer	Fabric/carbon/fabric (Lifetex, Saratoga)	Gas/vapor penetration
Coated fabrics	Woven fabric coated with rubber or plastic on one or both sides	PVC/nylon Polyurethane/nylon Neoprene/Nomex Butyl/Nylon/Butyl	Liquid splash, liquid or gas/vapor permeation
Plastic laminates	Plastic film laminated to one or both side of nonwoven fabric	Polyethylene/Tyvek* Tychem SL, BR, TK CPF I, II, III, IV Responder, Responder Plus	Liquid splash, liquid or gas/vapor permeation
Combination or specialized	Combines one or more of above material technologies or uses unique materials	Neoprene/nylon/neoprene/plastic laminate (VPS) Teflon/fiberglass/Teflon (Challenge)	Liquid splash, liquid or gas/vapor permeation

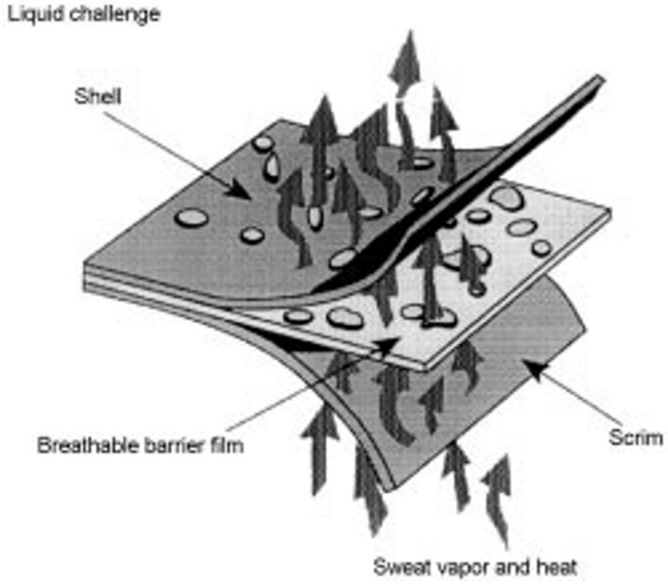
* Fabric is actually coated with polyethylene

Unsupported rubber and plastic materials

Normally, chemical protective clothing materials include supporting textile fabrics to provide strength. However, there are some CPC materials that do not include a fabric substrate. The rubber material or plastic is thick enough to provide sufficient strength for clothing use. Examples of polymers used in these materials are polyvinyl chloride and chlorinated polyethylene. Because the materials are continuous, they offer a barrier to liquids and can be used in the construction of CPC intended for protection against liquids and gases.

Microporous film-based materials

A relatively new class of CPC materials uses microporous films. As the name implies, microporous films have millions of microscopic pores per square inch of the film structure. In most cases, the pores are irregularly shaped with tortuous paths through the film. These pores are small enough to prevent the passage of most liquids, but still allow vapors and gases to pass through the material (see Fig. 12.2). This material feature makes the film 'breathable' and this feature is considered desirable for specifically allowing moisture vapor to transfer through chemical protective clothing to lessen the effect of wearer heat stress. The microporous films are generally glued or laminated to woven or nonwoven fabrics for physical support. Owing to their physical structure, these



12.2 Configuration of microporous material for providing liquid barrier performance and breathability.

fabrics provide barrier performance against liquids but not gases. The type of liquids held out by microporous materials will depend on the surface tension, as lower surface tension liquids penetrate easier than higher surface tension liquids.

Adsorbent-based materials

One class of CPC materials uses adsorbents added to textile layers for providing chemical protection against hazardous vapors or aerosols. These engineered materials include adsorbents, such as activated charcoal or other sorbent materials. The principle of material operation is similar to cartridges used in air-purifying respirators. The outer and inner layers of these fabrics are treated with a liquid repellent to limit liquid contact that can saturate the adsorbent layer. For the most part, these materials have been used in military applications for protection against chemical warfare agents. In general, these materials can be optimized for adsorbing different chemical classes, but generally are most effective for large-molecule chemicals.[7]

Coated fabrics

Up until the mid-1980s, the majority of chemical protective clothing used coated fabrics. Woven fabrics such as cotton, nylon, and polyester are coated with a polymer such as butyl rubber, neoprene, polyvinyl chloride, or polyurethane to provide a continuous coating over the fabric substrate. Coating thickness is important for barrier performance. Coatings that are too thin may be prone to pinholes and other defects. For some materials, coating may be applied to both sides to create a thicker and more chemically resistant material. Materials using this construction tend to be heavy, but relatively rugged and are used in a variety of chemical protective clothing. Today, the most common clothing using coated fabrics are splash suits, but some higher-end totally encapsulating suits may be made from coated fabrics. Reusable splash clothing is similar to rainwear.

Plastic laminates

The majority of chemical protective clothing today uses plastic laminates. These materials combine various plastic polymer films with nonwoven substrate fabrics resulting in chemical-resistant, lightweight, relatively inexpensive materials. The majority of substrates are based on polypropylene and films are based on polyethylene and polyvinyl alcohol polymers, but more sophisticated films may employ a variety of different plastic films in a single laminate. Like coated fabrics, the plastic layer may be applied to one or both sides of the fabric substrate. Materials with plastic film on both sides tend to provide greater chemical resistance at the expense of increased stiffness.

Combination or specialized materials

This category includes chemical protective clothing materials not fitting into the classes above. These fabrics generally attempt to combine the best attributes of each class. For example, coated fabrics have been laminated with a plastic film on one side to provide the flexible features associated with rubber-based fabrics and the high levels of chemical resistance. Microporous films can be combined with adsorbent-based materials to provide a film with liquid chemical resistance that adsorbs large molecular weight chemical vapors. One unique special material developed was based on applying Teflon to woven or nonwoven fiberglass substrate fabrics.

12.3.3 Garment design features

In addition to material choices, features affecting the design of garments include:

- the type and location of seams
- the type, length, and location of the closure system(s)
- the type and characteristics of visors or faceshields, if integrated into garments
- the design of interface areas with other chemical protective clothing or equipment
- the types, function, and location of hardware.

Seams

Seams play a critical role in protective clothing because they directly affect the integrity of the CPC in providing protection against specific chemical challenges. General types of seams used in chemical protective clothing include:

- sewn
- glued
- sealed.

Seams may also be bound or reinforced with other material pieces such as additional fabric or tape, or even covered with a top coating of a polymer.

The type of seam and how it is applied is usually affected by the material used in the garment construction and the intended integrity or performance of the chemical protective clothing:

- Sewing can be applied to any textile-based material.
- Gluing is usually performed for coated fabrics and unsupported rubber materials.
- Sealing is applied to materials where the surface can be melted to create a bond with the surface of another material. This seaming approach is used for

plastic laminates, thermoplastics, and other film-based materials. Sealing can be accomplished by using heat, ultrasonic radiation, or other means.

Different seam constructions can be used in protective clothing. A serged seam construction is popular for many styles of dry particulate-protective clothing because of its simplicity. However, lap or fell seams are also used in the fabrication of some CPC. Many CPC seams are sewn to provide garment strength against the stresses of wear and use. However, sewing by itself produces stitching holes that can provide a pathway for chemical penetration. Therefore, some seams will be bound for limiting these pathways for chemical penetration. Further protection of a sewn seam can occur when strips of tape directly cover the holes. The tape can be applied by either glues or by sealing the extra material over the seam. In some cases, seams are taped on both sides to provide increased chemical resistance.

The location of seams is also important. Not only do a large number of seams increase the garment manufacturing cost but also more seams can create potential exposure to the wearer in the event of seam failure. Therefore, some clothing designs are created to limit the number of seams and seams that are on the front of the garment where most chemical exposures occur.

Closure systems

Closures are typically the ‘weak’ link in the chemical protective clothing barrier. Closures are necessary to allow people to don and doff CPC, but should also not lower the integrity provided by the clothing. The simplest closures are zippers or a series of snaps. Because of the open construction of these closures and their needed placement often on the front of the garment, pathways for chemical penetration can be created. For this reason, many chemical protective clothing designs use storm flaps to cover the zipper or snaps. An extra storm flap on the interior side of the zipper can provide additional liquid protection. On many disposable or limited-use CPC, adhesive strips may be incorporated into the storm flap to keep it in place. Reusable CPC sometimes uses hook and loop closure tape to secure storm flaps or as the principal closure system.

Closure systems offering increased integrity against chemical penetration include liquid-repellent zippers, two-track extruded closures and special pressure-sealing zippers. Liquid-repellent zippers are conventional zippers that use rubber or plastic coated tape instead of woven cloth on the sides of the zipper and that have a special chain (teeth) that are coated to limit liquid penetration.

Two-track closures involve two extruded pieces of plastic that fit together to provide a seal much like many plastic sandwich bags. These closures offer good integrity against liquids (and vapors) but can be difficult to seal over a long length as might be required in a full-body garment. Some two-track closures use a zipper-like pull to seal the length shut but this design still leaves part of the end open. In addition, the types of plastics that work well for these closures are also limited and may not have chemical resistance compatible with the garment material.

The pressure-sealing zipper uses a compressible rubber or plastic material with a zipper chain to push the two sides of the closure material together for creating a seal. These zippers tend to be bulky and expensive but are generally required when total encapsulation of the wearer is required. As with seams, the location of the closure will be important. In some cases, the conventional design will feature the closure to be in the front of the garment. Some items such as totally encapsulating suits can have closures on the side or rear of the clothing item.

Garment visors

Visors are generally incorporated into separate hoods, coveralls, or suits to offer chemical barrier protection for the head and face area. In general, the visor is constructed from a material that provides clear undistorted vision as well as chemical resistance. While having some physical integrity, visors generally do not offer the same physical impact resistance provided by face shields and other primary face protection.

Garment visors vary in their size, stiffness, materials, and method of integration with the garment.

- The size of the visor affects the wearer's peripheral vision. In some garment designs, such as totally encapsulating suits, visor size has a significant effect on the wearer's field of vision since the suit visor does not move with the wearer's head. Consequently, more recent designs of these garments provide extra-large visors. This is less of a problem for hoods, which will rotate when the wearer turns his or her head.
- Visors can be flexible or rigid. Reusable suits and garments tend to use stiffer visors since overall weight may be less of a consideration, while many disposable garments incorporate relatively flexible visors to maintain low weight.
- The principal materials used in visor construction are polyvinyl chloride, polycarbonate, and polymethacrylate. Since the visor material must provide optical qualities, only transparent materials can be chosen as visors. When greater chemical resistance is required, the visor made be made of a composite material that includes fluorinated ethylene propylene (FEP) laminated to PVC. The FEP layer is kept thin because the material becomes opaque at large thicknesses, while the PVC provides support and scratch resistance.
- The joint between the visor and the garment is important for maintaining the integrity of the garment item. In some cases, the visor material is directly sealed to the garment material. In other cases, the visor may be perforated and

sewn in place, and then the seam is covered with tape. Some more robust designs for reusable clothing may use a gasket material to seal a rigid visor into a frame.

The visors used in suits, including the seams for integrating the visor in the garment, should be evaluated for the same properties as garments. These properties are important in addition to optical properties (such as visor clarity, light transmittance, and haze) that are specific to the visor. However, industry practice has typically not included chemical resistance of visors. At an incident in Benicia, California, United States in the mid 1980s, the failure of the visor in a totally encapsulating suit illustrated the potential life-threatening consequences of a visor failure. In particular, a leaking tank car of anhydrous dimethylamine required the response of a hazardous-materials team for incident evaluation and mitigation. Though the suit was recommended as being compatible with the leaking chemical, the visor of one responder's broke open during the incident. Fortunately, the self-contained breathing apparatus (SCBA) inside the suit protected the man's respiratory tract, but his unprotected skin was exposed to the dimethylamine. An analysis of the incident by the National Transportation Safety Board found that the polycarbonate visor material was unsuitable for dimethylamine exposure, though the suit itself was recommended.

Interface areas

The interfaces between the chemical protective clothing item and other CPC or equipment can vary with the design. Principal CPC interfaces include:

- amount of overlap for multi-piece garments
- upper torso garment sleeve to glove
- lower torso pant cuff to footwear
- upper torso garment collar to hood
- hood to respirator.

If different pieces of chemical protective clothing are worn, the items should provide sufficient overlap to cover the wearer's skin particularly during reaching or bending over. This is particularly an issue for jacket and pants sets of CPC.

The sleeve ends for garment-to-glove interfaces include a number of designs:

- For garments where there are no integrity issues, the sleeve end may be open. For a reusable garment, the sleeve end is hemmed; a disposable garment sleeve may be unfinished. If liquid leakage in the sleeve to glove area is a concern, duct tape is used but not recommended for providing integrity against liquid penetration.
- Elasticized sleeve ends provide somewhat better conformance of the sleeve with the glove. This design feature is particularly common for disposable and limited use clothing. However, chemical penetration may still occur at the

interface. The application of tape provides only a questionable improvement of integrity for chemical liquids or vapors.
- For suits requiring a higher level of protection, the gloves are attached to the garment sleeve end either permanently or in a manner in which they can be detached. These designs often include the incorporation of a hard ring into the sleeve end. An additional section of material at the sleeve end may be formed over the glove to act as a ‘splash’ guard.

Similar approaches are used for the pant cuff bottom in the interface area with footwear:

- A straight cuff is used. The cuff is generally pulled over the boot to keep liquid from entering the top of the boot or footwear. Like gloves, tape is sometimes used to keep the cuff in place.
- An elasticized cuff is used on some garment leg ends. This helps the pant leg stay in place on top of the boots. Tape may also be used, but only as a temporary measure for keeping the pant leg over the footwear.
- Some lower torso garment designs may use a covered zipper at the bottom of the leg so that the wearer can more easily insert his or her foot with attached boot or shoe through the pant leg.
- The garment material is fashioned into a bootie that is attached to the bottom of the garment leg and is worn inside the footwear. Garment booties are then worn inside an outer boot. This design may then include a splash guard mounted at the bottom of the garment legs that pull over the top of the boots.

Hoods can involve multiple interface areas. If a separate item, the bottom of the hood may be required to interface with the top of an upper torso garment. Most often, the length and flare of the hood control this interface. The bottom of the hood may also have slits to accommodate the wearer’s shoulders. If without a visor, the hood will create the interface with the wearer’s respirator facepiece or eye/face protection. This interface will provide limited protection if without some device or aid to close the hood face opening around the device. For this reason, hoods often incorporate drawstrings or elastic, or may have some other feature to cinch the hood opening around the respirator facepiece. Hoods may also need to accommodate hard hats or other head protection and hearing protection.

12.3.4 Garment sizing

There are few uniform sizing practices for the design of chemical protective garments. The availability of sizing often depends on the specific type of the garment and the relative volume of garments sold by the manufacturer. Sizing may be based on individual measurements for custom sizing, numerical sizing for regular wearing apparel (chest or waist size), or alphabetic sizing (e.g., small, medium, and large). Partial body garments are likely to be offered in fewer sizing choices. For example, sleeve protectors may vary in three lengths, while two sizes of aprons will be available, and only one size of hood is provided. It is important to realize that garment sizing must often take into account that the garment will be worn over regular work clothing and may need to accommodate different kinds of equipment, such as respirators, hard hats, and other devices.

Some sizing systems for garments usually use two or more wearer dimensions, such as height and weight, or height and chest circumference. This practice allows the wearer to determine the correct size by using their body dimensions. Unfortunately, sizing between manufacturers is often inconsistent. Even a standardized sizing scheme such as the one provided in ANSI/ISEA 101 for disposable or limited use coveralls has not found widespread acceptance among manufacturers. In addition, the sizing of protective garments often does not address the needs of women and special worker populations.[8]

12.4 Garment material chemical resistance testing

Chemical resistance is the principal basis on which CPC performance is based. Material test approaches can be classified into three types that describe how chemicals may interact with materials: degradation resistance; penetration resistance, and permeation resistance. A number of different procedures exist for the measurement of each type of performance depending on the type of chemical challenge and the level of sophistication for performing the tests. Of the material testing approaches, both penetration and permeation resistance testing allow assessment of the barrier qualities of a protective clothing material, whereas degradation resistance does not. Penetration testing may involve chemical particles, liquids, or vapors (gases). The individual procedures available for measuring chemical degradation, penetration, and permeation resistance are described in the subsections below.

12.4.1 Chemical degradation resistance

Degradation is defined as the ‘change in a material’s physical properties as the result of chemical exposure.’ Physical properties may include material weight, dimensions, tensile strength, hardness, or any characteristic that relates to a material’s performance when used in a particular application. As such, the test is used to determine the effects of specific chemicals on materials. In some cases chemical effects may be dramatic showing clear incompatibility of the material with the chemical. In other cases, chemical degradation effects may be very subtle.

Various groups have examined different approaches for measuring the chemical degradation resistance of barrier materials, but no single generalized test method has been developed by consensus organizations within the United States, Europe, or internationally that can apply to all protective clothing materials.[9] Nevertheless, a variety of techniques are commonly used for rubber and plastic materials within different barrier material industries. These procedures and their utility in evaluating chemical barrier materials are discussed below.

Degradation tests using immersion-based techniques

ASTM D 471 and D 543 establish standardized procedures for measuring specific properties of material specimens before and after immersion in the selected liquid(s) for a specified period of time at a particular test temperature. Test results are reported as the percentage change in the property of interest. ASTM D 471 provides techniques for comparing the effect of selected chemicals on rubber or rubber-like materials, and is also intended for use with coated fabrics. ASTM D 543 covers testing of plastic materials, including cast and laminated products, and sheet materials for resistance to chemical reagents. In each test, a minimum of three specimens is used whose shape and size are dependent on the form of the material being evaluated and the tests to be performed. An appropriately sized vessel, usually glass, is used for immersing the material specimens in the selected chemical(s). Testing with volatile chemicals typically requires either replenishment of liquid or a reflux chamber above the vessel to prevent evaporation.

Both test methods indicate that the selected exposure conditions and physical properties measured should be representative of the material's use. For CPC material testing, this will usually mean specifying significantly shorter test periods and ambient temperature exposures. Since the methods are intended for comparing materials against similar chemical challenges, no criteria are given for determining acceptable performance.

Degradation tests using one-sided exposure techniques

Section 12 of ASTM D 471 provides a procedure for evaluating the effects of chemicals when the exposure is one sided. This technique is particularly useful for the evaluation of protective clothing materials, particularly those involving coated fabrics, laminates, and any non-homogeneous material. In this procedure, the material specimen is clamped into a test cell that allows liquid chemical contact on its normal external (outer) surface. Usually, changes in mass are measured for this testing approach since the size of the material specimens is limited.

ASTM F 1407, while intended for measuring chemical permeation resistance, also serves as a useful technique for evaluating chemical degradation resistance of protective clothing materials.[10,11] This test employs a lightweight test cell in which the material specimen is clamped between a Teflon-coated metal cup filled with the selected chemical and a metal ring (flange). The entire cup assembly is inverted and allowed to rest on protruding metal pins that hold the test cell off the table surface. In the permeation testing mode, the weight of the entire assembly is monitored; however, for use as degradation test, the test cell serves as a convenient means for evaluating changes in material mass and thickness. Visible observations are also recorded as part of the testing protocol.

The International Safety Equipment Association undertook the development of a degradation resistance test method for providing a means to evaluate and classify glove performance in a new standard specific for hand protection (ANSI/ISEA 105). The test is based on the principle of one-sided exposure, employing a small flask containing the test chemical. The CPC specimen is sealed to the top of the flask and the flask is inverted to allow the test chemical to contact the specimen for a period of one hour. The flask is then positioned upright and mounted in a tensile testing machine outfitted with a compression cell and puncture probe. This test apparatus is used to measure the force required to puncture the specimen. The puncture resistance of exposed samples is then compared to the puncture resistance of pristine specimens. The percentage change in puncture resistance can thus be used as a measure of glove material degradation resistance to specific chemicals.

Application of test data

Chemical degradation by itself cannot fully demonstrate product barrier performance against chemicals. While a material that shows substantial effects when exposed to a chemical can be ruled out as a protective material, it remains uncertain whether materials that show no observable or measurable effect act as a barrier against the test chemical. For this reason, chemical degradation data are typically used as a screening technique to eliminate a material from consideration for further chemical resistance testing (i.e., penetration or permeation resistance).[12] Some sample degradation resistance data are shown in Table 12.5 comparing three different materials and three different methods of discerning degradation effects.

The majority of chemical degradation resistance data are reported in the glove industry. This is because most gloves are made from elastomeric materials. As a class of materials, elastomers when compared to plastics, show greater affinity for chemical adsorption and swelling.[13] Therefore, elastomeric materials are generally more susceptible to measurable chemical effects. This is particularly true today, because the majority of garment materials are composed of different plastic layers that have few observable degradation effects.

12.4.2 Chemical penetration resistance

Penetration is defined as ‘the flow of chemical through closures, porous materials, seams, and pinholes and other imperfection in a protective clothing material on a non-molecular level.’ This definition is intended to accommodate

Table 12.5 One-sided immersion degradation resistance data for selected materials and chemicals

Chemical	Viton/chlorobutyl laminate			Chlorinated polyethylene			FEP/surlyn laminate		
	Percent weight change	Percent elong.[a] change	Visual obs.	Percent weight change	Percent elong. change	Visual obs.	Percent weight change	Percent elong. change	Visual obs.
Acetaldehyde	10	0		24	11		0	−5	
Acrylonitrile	9	0	delam.	35	failed		−1	0	
Benzene	2	0		60	failed		0	0	
Chloroform	4	0		72	failed		0	0	
Dichloropropane	3	0		120	failed		−2	0	
Ethyl acrylate	17	0	curled	160	failed		0	0	
Ethylene oxide	2	0		13	11		0	0	
Hydrogen fluoride	4	0	discol.	2	11	discol.	4	0	
Nitric acid	9	0	discol.	8	−6		−1	0	

Abbreviations: FEP – Fluorinated ethylene propylene; elong. – tensile elongation; obs. – observations; delam. – delaminated; discol. – discolored.

[a] Percent elongation based on elongation measured using ASTM D412 for exposed and unexposed samples, 'failed' results indicate materials not tested due to weight changes over 25%.

Source: adapted from ref. 12.

both liquids and gases, but all U.S., European and International test methods focus on liquid penetration. Liquid suspended in air as aerosols and solid particles can also penetration protective clothing materials, but the discussion of penetration resistance in this section relates to liquids exclusively because particle-based test methods for CPC are still under development.

Liquid repellency and penetration resistance are related since wettability of the fabric affects the ability of the liquid to penetrate. For porous fabrics, a liquid of surface tension, γ, will penetrate given sufficient applied pressure, p, when its pores are of diameter, D, according the relationship known as Darcy's Law:

$$D = k\frac{4\gamma\cos\theta}{p} \qquad 12.1$$

where: θ = contact angle of liquid with the material, and k = shape factor for the material pores. For non-porous fabrics, particularly coated fabrics or laminate materials, liquid penetration may still take place as the result of degradation. Given a sufficient period of contact, chemicals may cause deterioration of the barrier film to allow pathways for liquid to penetrate. In this sense, penetration testing allows both an assessment of material barrier performance to liquid chemicals and chemical degradation resistance. There are two fundamentally different approaches used in liquid penetration resistance test methodologies, runoff-based methods, and hydrostatic-based methods. Table 12.6 compares the different characteristics of these test methods.

Runoff-based penetration tests

Runoff-based techniques involve contact of the liquid chemicals with the material by the force of gravity over a specified distance. The driving force for penetration is the weight of the liquid and the length of contact with the material specimen. Usually, the material specimen is supported at an incline, allowing the chemical to run off, hence the name for this class of penetration tests. Runoff-based tests are characterized by three features:

- impact of the liquid from a stationary source onto a material specimen
- orientation of the material specimen at an incline with respect to the point of liquid contact
- use of a blotter material underneath the material specimen to absorb penetrating liquid.

Runoff-based tests differ in the distance separating the liquid source from the point of contact with the material specimen, the type of nozzle through which liquid is delivered, the amount of liquid, the rate at which the liquid is delivered, the angle of the incline, and the type of test measurements made. The majority of these methods are intended for use with water as the liquid challenge only. Physically, many of the methods are suitable for testing with other liquids;

Table 12.6 Characteristics of runoff-based and hydrostatic-based penetration resistance tests

Test method	Type of delivery	Liquid amount and rate	Sample orientation	Measurements
Runoff-based				
AATCC 42	Specified nozzle above specimen	500 ml delivered at distance of 0.6 m	45 degrees, over blotter	Weight gain of blotter
ASTM F 2130	Applied through pipette	0.1 or 0.2 ml	Horizontal, over blotter	Weight gain of blotter
EN 368	Single, 0.8 mm bore hypodermic needle 100 mm above sample	10 ml at 1 ml/sec	45 degrees, over blotter in semicircular 'gutter'	Index of repellency; Index of penetration
ISO 6530	Same as EN 368			
ISO 22608	Same as ASTM F 2302			
Hydrostatic-based				
AATCC 127	Water pressurized above specimen at constant rate	Water pressure increased at rate of 10 mm H_2O/sec	Horizontal, clamped in test apparatus	Pressure at which water droplets appear in three separate specimen locations
ASTM D 751, Method A	Water pressurized above specimen at constant rate	Water pressure increased at rate of 1.4 ml/sec	Horizontal, clamped in test apparatus	Pressure at which water droplet appears
ASTM F 903	Liquid pressurized against specimen in test cell	60 ml liquid chemical, different pressurization options	Vertical, clamped in test cell	Visual observation of penetration
ISO 811	Water pressurized above specimen at constant rate	Water pressure increased at rate of 10 cm or 60 cm H_2O/sec	Horizontal, clamped in test apparatus	Pressure at which water droplets appear in three separate specimen locations
ISO 1420	Water pressurized underneath specimen at constant rate	Water pressure increase rate to be specified by lab	Horizontal, clamped in test apparatus	Pressure at which water droplet appears
ISO 13994	Same as ASTM F 903			

however, the containment aspects of these test methods vary and some are clearly inappropriate for use with hazardous chemicals. Some of the tests involve delivering relatively large quantities of water onto a sample and measuring the amount of water absorbed in a blotter paper placed underneath the material specimen. This approach is characteristic of AATCC 42. The large quantities of water specified, and the lack of containment in the design of the apparatus make these test methods unsuitable for other liquids.

Two of the test methods are essentially identical and are designated for use with various liquid chemicals. Both EN 368 and ISO 6530, the so-called ‘gutter test,’ use a system where the liquid chemical is delivered by a single, small-bore nozzle onto the material specimen at a distance of 100 mm. The material is supported in a rigid transparent gutter which is covered with a protective film and blotter material set at a 45 degree angle with respect to the horizontal plane. A small beaker is used to collect liquid running off the sample. The two results reported in these tests are the indices of penetration and repellency. The index of penetration is the proportion of liquid deposited in the blotter paper:

$$\text{Index of penetration } (P) = \frac{M_p \times 100}{M_t} \tag{12.2}$$

where M_p is the mass of test liquid deposited on the absorbent paper/protective film combination and M_t is the mass of the test liquid discharged onto the test material specimen.

The index of repellency is the proportion of liquid deposited in the blotter paper:

$$\text{Index of repellency } (R) = \frac{M_r \times 100}{M_t} \tag{12.3}$$

where M_r is the mass of test liquid collected in the beaker. A mass balance of the liquid also allows calculation for liquid retained in the material specimen. Variations of the runoff tests applied to the pesticide formulations are found in ASTM F 2130 and ISO 22608. Not all of the tests described above can be considered ‘true’ liquid penetration tests. Penetration with these procedures can only be characterized when some assessment or measurement of liquid passing through the material specimen is made. Typically this is done by examination of the blotter material, either visually or gravimetrically.

Runoff tests are generally used on textile materials which have surface finishes designed to prevent penetration of liquid splashes. Many of these tests easily accommodate uncoated or non-laminate materials, since the driving force for liquid penetration is relative low (when compared to hydrostatic-based test methods). As a consequence, runoff tests may be infrequently specified for chemical barrier-based clothing. The relatively small amount of liquid involved in some runoff tests is not considered a strong challenge. ISO 6530 recommends that the test be used only when the clothing item’s overall integrity for preventing liquid penetration has been demonstrated. A discussion of liquid-based integrity methods appears later in this chapter.

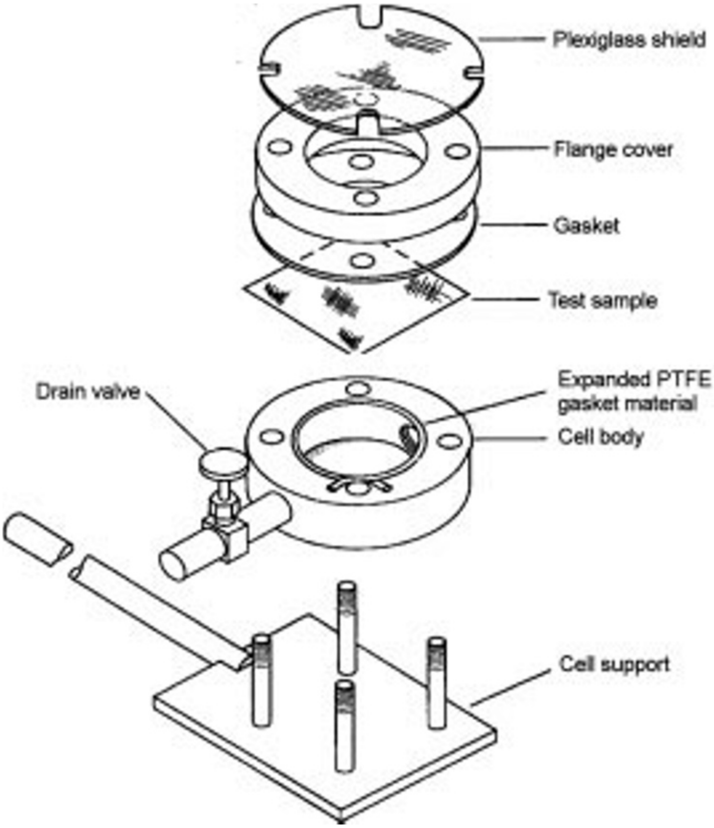
Hydrostatic penetration testing

Hydrostatic-based techniques involve the pressurization of liquid behind or underneath the material specimen. It is this hydrostatic force which is the principal driver for liquid penetration. In this testing approach, liquid is contacted with the material specimen, with at least some portion of the test period having the liquid under pressure. Different devices or test cells are available for providing this type of liquid contact with the material specimen, in essence representing the differences among representative test methods. Like runoff-based test methods, the majority of the industry tests are designed for use with water. Many of the devices described below cannot be used with other liquids or may even be damage if anything but water is used in the respective tests.

Two different types of testing machines prevail for measuring hydrostatic resistance. AATCC 127 and ISO 811 use similar devices, where water is introduced above the clamped material specimen at a pressure controlled by water in a rising column. A mirror is affixed below the specimen to allow the test operator to view the underside of the specimen for the appearance of water droplets. Both the pressure and length of exposure are to be specified for the particular application. AATCC 127 defines water penetration as the pressure when a drop or drops appear at three different places of the test area (on the specimen). When a specific hydrostatic head is specified, test results are reported as pass or fail. ASTM D 751 and ISO 1420 use a motor-driven hydrostatic tester. Water contacts the underside of the material specimen that is clamped into a circular opening. Increasing hydraulic pressure is applied to the clamped material specimen at a specified rate until leakage occurs. The pressure at which this leakage occurs is noted and reported as the test result.

Of the listed tests above, only ASTM F 903 and ISO 13994 were developed for testing liquids other than water.[14] In these test methods, a 70 mm square material specimen is exposed on one side to the test chemical for a specified period of time using a special penetration test cell (see Fig. 12.3). The test cell is positioned vertically to allow easy viewing of the material specimen. During the chemical exposure, a pressure head may be applied to the liquid for part of the test period. Penetration is detected visually and sometimes with the aid of dyes or fluorescent light. The test is generally pass/fail, i.e., if penetration is detected within the test period, the material fails. Observations of material condition following chemical exposure are also usually provided. Different test specifications exist for the amount of chemical contact time and level of pressurization.

Penetration resistance using a hydrostatic-based test methods can accommodate a variety of different material types and clothing test specimens,



12.3 Exploded view of ASTM F 903 penetration test cell.

including CPC seams and closures. For these types of material specimens there are different modes of failure. Continuous film or film coated fabrics generally fail only due to imperfections in the material, such as cuts or pinholes or deterioration (degradation) of the film providing an avenue for liquid penetration. The latter type of failure often depends on the thickness of the film or coating as well as the contact time and amount of pressure applied to the specimen.

Textiles and microporous film products provide another set of possible failure mechanisms. Textiles may be considered as a liquid barrier when they have been treated with water/chemical repellent finishes. The ease of liquid penetration is therefore more a function of repellent finish quality and the surface tension of the liquid being tested. Also, penetration may still be the result of material degradation while in contact with the chemical. Microporous film products represent a unique test material since by design they afford transmission of vapors but prevent liquid penetration. These materials therefore require careful observations since significant vapor penetration may occur. Like textiles, surface tension may be a factor, though most microporous films have pore sizes that preclude penetration of most common liquids at relative low pressures (less than 12 kPa).

The integrity of seams, closures, and other clothing material interfaces are easily evaluated using penetration resistance testing.[15,16] Their uneven sample profiles must be accommodated through special gaskets or sealing techniques. For zipper closures, a groove has been cut in the test cell to provide a better seal on the protruding teeth portion of the zipper. In assessing penetration resistance for these items, failures may occur because of

- penetration of liquid through stitching holes in seams
- solvation of seam adhesives
- degradation of seam tapes or other seam components
- degradation of materials joining seam causing lifting of seam tapes or destruction of seam integrity
- physical leakage of closures.

Berardinelli and Cottingham[15] demonstrated the utility of this test on a number of material, seam, and closure samples. Understanding how clothing specimens may fail provides insight into identifying protection offered by the overall clothing item.

Specific use of penetration resistance tests

Penetration testing as per ASTM F 903 (and ISO 13994) provides a test for assessing the barrier performance of materials against liquid chemicals.[16] Though measuring specimen weight change is not required, this testing can also serve to measure material degradation since visual observations are required. In turn, degradation of the material may be a primary route for penetration by some chemicals. The difficulty in penetration testing lies in making a clear cut determination of liquid penetration. Many high vapor pressure, low surface tension solvents spread thinly over the material and evaporate quickly. Therefore, actual liquid penetration may be difficult to observe even when enhanced by using dyes. Still, the test serves as a good indicator of material performance against liquid contact or splashes. Since test length and pressurization periods depend on the selected procedure within the method, pass/fail determinations are clear-cut and easily define acceptable material-chemical combinations.

ASTM F 903 and ISO 13994 incorporate four types of contact time and pressure exposure formats (see Table 12.7). The original protocol consisted of exposing the material to the liquid for a five-minute period at ambient pressure, followed by a ten-minute period at 13.8 kPa. This exposure condition was selected as a test pressure to simulate the force on a protective garment of a liquid coming out of a burst pipe at an approximate distance of 3 m. A lower

Table 12.7 ASTM F 903/ISO 13994 penetration test variations

Procedure	Initial contact period (minutes at 0 kPa)	Pressurization period (minutes/pressure)	Subsequent contact period (minutes at 0 kPa)
A	5	10 min/7 kPa	None
B	5	10 min/14 kPa	None
C	5	1 min/7 kPa	54
D	60	None	None

pressure of 6.9 kPa was adopted later on because many materials would 'balloon' away from the test cell as pressure was applied. Some differences in material performance due to degradation effects have been noted as shown in Table 12.8.[14] The additional contact time/pressure formats in ASTM F903 were included to accommodate practices being used by the National Fire Protection Association in their requirements for chemical protective suit material and component penetration resistance.[17] Many unsupported film samples cannot be tested at high pressure since they burst when the pressure is applied. In these cases, the true barrier properties of the material to liquid penetration are not tested. For this reason, the optional use of a screen having more than 50% open area is specified in ASTM F 903 and ISO 13994 to prevent over-expansion of the clothing material specimen.

12.4.3 Permeation resistance

Permeation is a process in which chemicals move through a material at a molecular level. Material permeation resistance is generally characterized using two test results: breakthrough time and permeation rate. Breakthrough time is

Table 12.8 Effect of contact time and pressure on penetration of selected material-chemical combinations

Material	Chemical	Penetration test exposure protocol	Penetration time (minutes)
PVC/Nylon	Dimethylformamide	A	None
		B	None
		C	40
		D	50
Microporous film/ nonwoven laminate	Hexane	A	None
		B	5
		C	5
		D	None

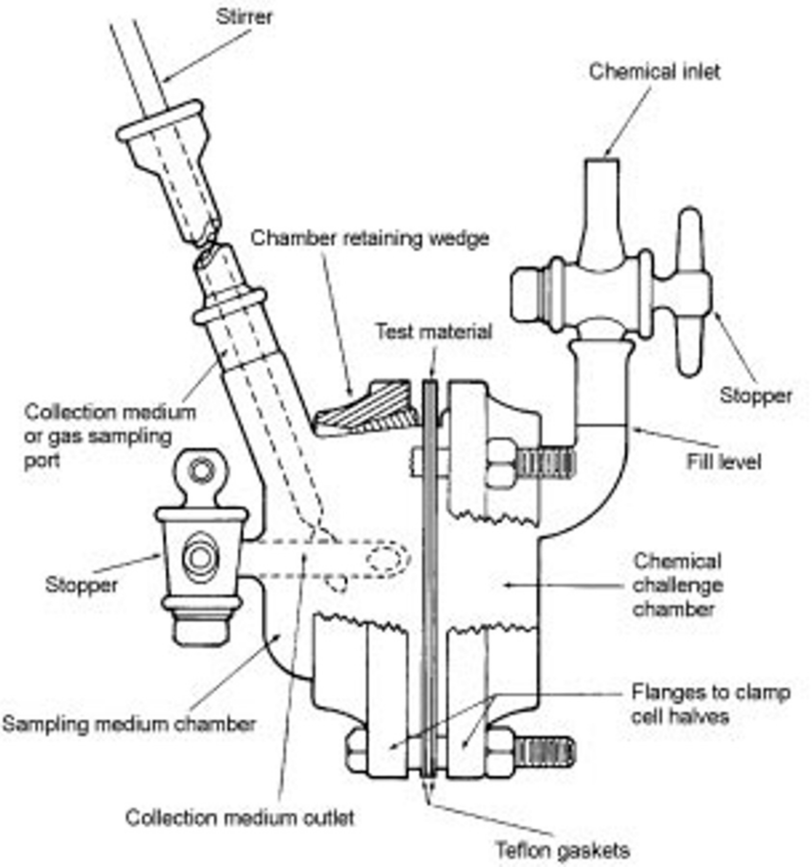
Source: Adapted from ref. 16.

the time that chemical is first detected on the 'interior' side of the material. As discussed below, its determination is strongly dependent on how the test is configured and the sensitivity of the detector. Permeation rate is a measure of the mass flux through a unit area of material for a unit time. Permeation rate is most commonly expressed in units of micrograms per square centimeter per minute (μg/cm^{2}min). For a given material-chemical combination, the steady-state or maximum observed permeation rates are reported. The measurement of chemical permeation resistance is specified in different standard test methods offered by ASTM, CEN, and ISO.

These permeation tests involve either liquid or gaseous chemical contact with the material and assessment of permeation as affected by both chemical solubility and diffusion through the test material. ASTM F 739 was first established in 1981 as the first test standard test method for measuring material permeation resistance to liquid chemicals.[18] ASTM F 739, EN 369, and ISO 6529 provide standardized procedures for measuring the resistance of protective clothing to permeation by chemicals using continuous contact of the chemical with the material's exterior surface. ASTM F 1383 is a variation of ASTM F 739 that involves testing under conditions of intermittent chemical contact. ASTM F 1407 represents a simplified form of testing where permeation is determined gravimetrically. Based on its limited sensitivity, this method is primarily used as a screening test or field method. In each of the tests (except ASTM F1407), a similarly designed test cell is used for mounting the material specimen (Figure 12.4). The test cell consists of two hemispherical halves divided by the material specimen. One half of the test cell serves as the 'challenge' side where chemical is placed for contacting the material chamber. The other half is used as the 'collection' side that is sampled for the presence of chemical permeating through the material specimen.

The basic procedure in each test is to charge chemical into the challenge side of the test cell and to measure the concentration of test chemical in the test cell as a function of time. Of principal interest in permeation testing are the elapsed time from the beginning of the chemical exposure to the first detection of the chemical (i.e., the so-called breakthrough time), the permeation rate, and the cumulative amount of chemical permeated. The results reported are dependent on the test method chosen:

- ASTM F739 requires reporting of breakthrough time and maximum or steady state permeation rate.
- ASTM F1383 specifies reporting breakthrough time and cumulative permeation.
- ASTM F1407 permits reporting either cumulative permeation or breakthrough time and permeation rate (maximum or steady state).
- EN 369 requires reporting of breakthrough time with the total cumulative mass permeated at 30 and 60 minutes.



12.4 Specification for ASTM F 739 standard permeation test cell.

ISO 6529 combined ASTM and CEN approaches into its procedures. Other significant differences exist between the different listed test methods as described below. Table 12.9 provides a comparison of key characteristics for each of the different permeation test methods.

Parameters affecting permeation resistance testing

Although the permeation test procedure is simple in concept and generalized procedures are specified by each of the test methods above, a number of significant variations exist in the manner in which permeation testing can be conducted. These variables include:

- the general configuration of the test apparatus
- how the chemical contacts the material specimen in the test cell
- the type of collection medium used and frequency of sampling

Table 12.9 Differences between permeation test methods

Test method	Chemicals permitted	Type of contact	Collection medium flowrate(s)	Minimum test sensitivity (μg/cm^{2}min)	Test results reported
ASTM F 739	Liquids and gases	Continuous	50 to 150 ml/min	0.1	Breakthrough time Permeation rate
ASTM F 1383	Liquids and gases	Intermittent	50 to 150 ml/min	0.1	Breakthrough time Cumulative permeation
ASTM F 1407	Liquids only	Continuous	Not applicable	≈ 20.0*	Breakthrough time Permeation rate Cumulative permeation
EN 369	Liquids only	Continuous	520 ml/min (gas) 260 ml/min (liq.)	1.0	Breakthrough time Cumulative permeation at 30 and 60 minutes
ISO 6529	Liquids and gases	Continuous or intermittent	Not specified	0.1 or 1.0	Breakthrough time Permeation rate Cumulative permeation

* Depends on analytical balance, exposed specimen surface area, and time interval between measurements.

- the type of detector and detection strategy used
- the test temperature
- the effect of multicomponent solutions.

The variety of available test techniques and conditions allows several different approaches for conducting permeation testing and can provide different results for testing the same material and chemical combination. This apparatus should be configured to meet testing needs and accommodate the characteristics of the chemical(s) being tested. Test cells are generally specified by the test method, but alternative designs are available and may be necessary for testing with specific chemicals or chemical mixtures. Likewise, the chemical delivery and collection/detection systems are dependent on the nature of the chemical and the requirements for running the test. The way that each part of the apparatus is operated comprises the test apparatus configuration. There are two basic modes for configuring permeation test systems, closed-loop or open-loop.

In closed-loop permeation systems, the volume of collection fluid is maintained throughout the test. This volume may be contained fully within the collection chamber or it may be circulated through the chamber, into a non-intrusive detector, and back into the chamber. Since the total volume of collection medium remains constant, permeating chemical accumulates within the collection medium. In this system, the permeation rate must account for this accumulation of permeant as follows:

$$\text{Rate} = \frac{(C_n - C_{n-1})}{(t_n - t_{n-1})} \times \frac{V}{A} \qquad 12.4$$

where $(C_n - C_{n-1})$ is the change in concentration of the challenge chemical between sampling periods, $(t_n - t_{n-1})$ is the time between sampling periods, V is the volume of collection medium, and A is the exposed area of the material specimen.

In the open-loop permeation systems, a gas or liquid collection medium is passed through the collection side out of the test cell to the detection system. This collection medium stream can be evaluated discretely or continuously depending on the detector selected. Therefore, collection of permeant is specific to the sample taken (over a discrete time period) and permeation rates can be directly calculated as a factor of the collection medium permeant concentration (C) and flow rate (F):

$$\text{Rate} = \frac{C \times F}{A} \qquad 12.5$$

The choice of a closed- or open-loop system is most often determined by the properties of the chemical and the available detector. Some chemicals such as inorganic substances often require closed-loop systems, particularly if ion-specific electrodes are used which have recovery time constraints. Open-loop testing is preferred for many volatile organic chemicals because these systems can be easily automated.

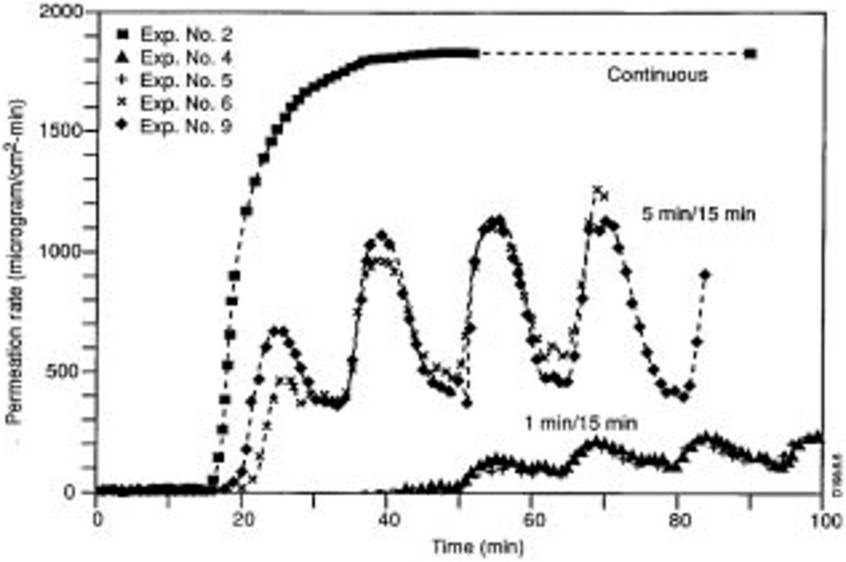
Permeation test methods are generally applied with neat chemicals under conditions of continuous exposure. In liquid exposures, the chemical or chemical mixture of interest is placed directly in the challenge portion of the test cell and left in contact with the material specimen for the selected duration of the test. ASTM F 739 and ISO 6529 permit testing with gases, using the modifications to the test cell. Special considerations are needed for testing of gases to ensure integrity of the test cell and proper disposal of the effluent challenge gas.[19,20] Permeation testing may also be conducted against vapors of liquid chemicals per ASTM F 739. These tests require a high level of temperature control to achieve consistency in the vapor concentration of the chemical and a different orientation of the test cell[19] and have shown ways of discriminating material performance as shown in Table 12.10. Some research has also been reported for conducting permeation tests with solids. Lara and Drolet[21] describe a modified test cell where a gel-containing nitroglycerin was placed on the surface of the material's external surface for permeation testing.

Intermittent forms of chemical contact akin to splash-like exposures are prescribed in ASTM F 1383 and ISO 6529. In these test methods, the time of material specimen exposure to chemical is varied in a periodic fashion. Chemical is charged into the challenge side of the test cell and then removed after a specified time. This type of exposure may be repeated in a cyclic fashion. The use of intermittent exposure conditions gives rise to permeation curves with a cyclic appearance (see Fig. 12.5). As a consequence, breakthrough time with cumulative permeation is reported in lieu of permeation rate for these tests. Schwope *et al.*[22] illustrated this behavior for a number of material-chemical combinations and found the cumulative permeation to be proportional to the relative exposure time. Man *et al.*[23] compared permeation breakthrough times of protective clothing materials against specific chemicals using liquid contact, liquid splashes, and vapors. Their findings showed significant differences between the different exposure conditions for some combinations of materials and chemicals, but lesser changes in breakthrough time for other material-chemical sets.

Table 12.10 Permeation data for chemical vapors for selected material-chemical combinations

Material-chemical combination	Chemical challenge	Breakthrough time (minutes)	Permeation rate (μg/cm^2 min)
Ethylene dichloride against PVC glove	Saturated vapor @ 27 °C	4	>25,000
	10 ppm in nitrogen	4	350
Dichloromethane against Viton-Butyl suit material	Liquid	16	470
	Saturated vapor @ 27 °C	28	280
	100 ppm in air	No BT	Not applicable

Abbreviation: No BT – no breakthrough observed in three-hour period for testing per ASTM F739.
Source: adapted from ref. 19.



12.5 Cyclic permeation observed during permeation test involving intermittent contact (from ref. 23).

The choice of collection medium, sampling frequency and detector are determined by the chemicals to be evaluated. For example, the collection medium must have a high capacity for the permeating chemical(s), allow ready mixing, be readily analyzed for the chemical(s) of interest, and have no effect on the clothing material being tested.[24] Air, nitrogen, helium, and water are common collection media. In general, these collection media have no effect on the clothing material and are amenable to most analytical techniques. In cases where the test chemical has a relatively low vapor pressure, other approaches must be used. One approach for conducting permeation tests with these chemicals has been to use solid collection media.[22,25] This technique involves placing a solid, highly absorbent film directly against the material specimen. Ehntholt[25] designed a special test cell successfully using a silicone rubber material for collection of pesticides. An alternative approach advocated by Pinnette, Stull *et al.*[24] and Swearengen *et al.*[26] has been the use of a liquid splash collection. In these approaches, a solvent media is briefly contacted with the material specimen on the collection side and the extract evaluated for the chemical(s) of interest. The design of test system will determine whether permeant can be analyzed continuously or at some frequency of sampling. Since breakthrough time is totally dependent on the sensitivity of the detector, a detector must be used that can provide determination of concentrations that yield sufficiently low permeation rates.

Effects of temperature

Spence[27] first showed significant changes in the permeation resistance of protective clothing materials with increasing temperature as evidenced by shorter breakthrough times and larger permeation rates. Changes in temperature may have an influence on permeation by several mechanisms. Increased temperatures may increase the concentration of the challenge chemical adsorbed onto the material surface by increasing the solubility of the material-chemical matrix or by increasing the vapor pressure of the chemical.[28] The rate of diffusion step in the permeation process may also increase with temperature following an Arrhenius equation type of relationship.[27–31] Temperature, therefore, exhibits its effect on breakthrough time and permeation rate through the diffusion coefficient (D) and solubility (S). The expected effect manifests itself in a logarithmic-like relationship between permeation rate and temperature. Figure 12.6 shows this relationship for several material-chemical pairs and temperatures. Even small differences in temperature have been shown to significantly affect permeation breakthrough times as shown in Table 12.11. As a consequence, permeation testing must be performed under tightly controlled temperature conditions.

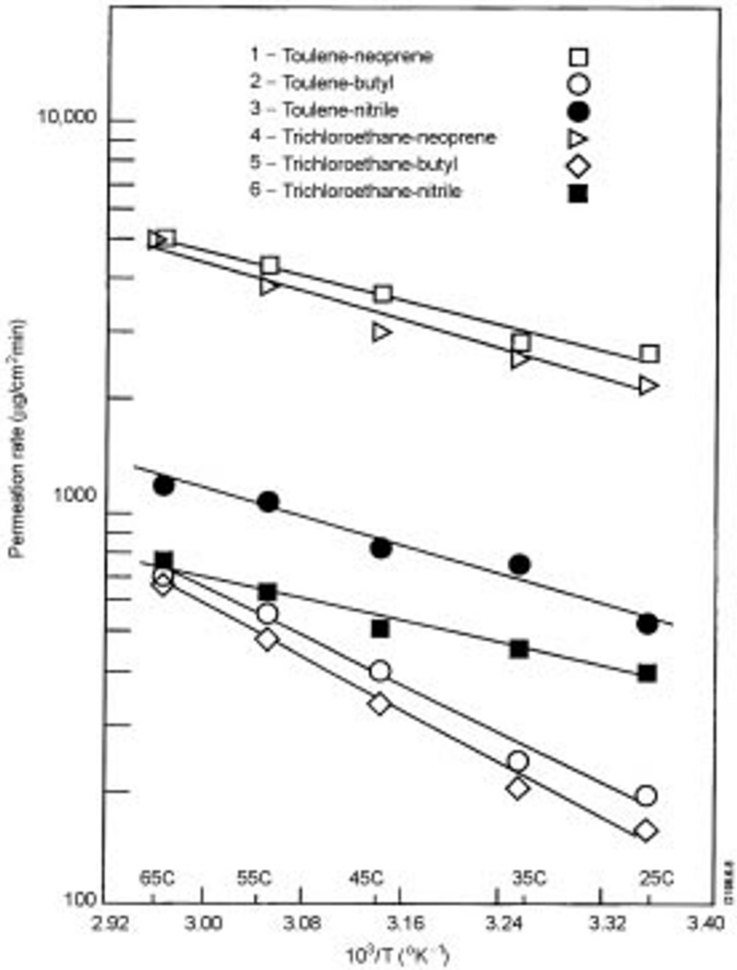
Effect of testing multi-chemical challenges

When permeation tests involve multi-chemical challenges, test configurations must employ detection techniques which permit the identification of each chemical in the permeating mixture. A number of researchers have investigated the effects of multicomponent chemical mixture permeation through barrier materials. Stampher *et al.*[32] investigated the permeation of PCB/paraffin oil and 1,2,4 trichlorobenzene mixtures through protective clothing. They used a small amount of isooctane in the collection medium to capture permeating PCBs. Schwope *et al.*[33] performed extensive testing with pesticides using different active ingredients and carrier solvents. Their tests demonstrated different breakthrough times and proportions of permeating chemicals between pesticide and carrier solvent. Bentz and Man[28] identified a case involving acetone/hexane

Table 12.11 Temperature effects on breakthrough time

Test material	Temperature (°C)	Acetone breakthrough time (minutes)
Viton/chlorobutyl laminate	20	95–98
	26.5	43–53
Chlorinated polyethylene	22	32–35
	24.5	27–31

Source: ref. 23.



12.6 Plot showing effect of temperature on permeation rate for selected material-chemical combinations (from ref. 31).

mixtures where the mixture permeated a dual elastomer coated material at shorter breakthrough times than either of the pure components. This testing illustrated the potential synergistic permeation of mixtures. Mickelsen, Roder, and Berardinelli[34] evaluated elastomeric glove materials against three different binary mixtures and found similar permeation behavior where mixture permeation could not be predicted on the basis the individual mixture components. Ridge and Perkins[35] attempted to model mixture permeation using solubility parameters and found the technique to be only partially successful. Goydan *et al.*[36] were able to predict the mixture using a series of empirical rules when applied to a particular fluoropolymer laminate material.

Use and interpretation of permeation testing

As originally indicated, breakthrough time and steady-state or maximum permeation rate are typically provided as permeation test data. ASTM F 739 as well as CEN and other test methods also require reporting of key test parameters. In general, these include a complete description of the test material, test chemical, and test system configuration. Table 12.12 lists test parameters that should be reported with each test. ASTM F 1194 provides a more extensive list of testing reporting requirements

Since sensitivity significantly affects breakthrough times, ASTM, CEN, and ISO have adopted reporting requirements which are intended to normalize the effect of test system parameters on this measurement. Currently, ASTM F 739 and ASTM F 1383 specify reporting of the 'normalized' breakthrough time in additional to actual breakthrough time. Normalized breakthrough time is defined as the time when the permeation rate is equal to 0.10 μg/cm^{2}min. European test methods specify reporting breakthrough times at the time the rate equal 1.0 μg/cm^{2}min, a single order of magnitude difference with U.S. test methods. ISO 6529 permits both approaches. Therefore, it is important that permeation breakthrough time data be compared only when the respective sensitivities of the test laboratories are the same or if data is normalized on the same basis.[37]

Permeation resistance testing is the appropriate test when vapor protection is required. This does not mean that the test can only be applied for gas or vapor challenges, but rather that the test discriminates among chemical hazards at a

Table 12.12 Permeation test report parameters

Area	Reporting requirements
Test chemical	Components Concentration Source
Test material	Identification Source Condition at time of testing Thickness Unit area weight
Test system	Overall configuration (open or closed loop) Type of test cell Type of challenge (continuous or intermittent) Collection medium Collection medium flow rate Detector or analytical technique
Test results	Breakthrough time Normalized breakthrough time Test system sensitivity Steady-state or maximum permeation rate Cumulative permeation

molecular level owing to the sensitivity for detecting a permeating chemical in its vapor form (as opposed to liquids or solids). As such, permeation testing represents the most rigorous of chemical resistance test approaches. Table 12.13 shows representative permeation and penetration resistance data for selected materials and chemicals.

Within the protective clothing industry, many end users judge the acceptability of a material on the basis of how its breakthrough time relates to the expected period of exposure. Reporting of permeation rate offers a more consistent and reproducible means of representing material permeation. The inherent variability and test system dependence on breakthrough times make these data a less than satisfactory choice for characterizing material performance. Permeation rate data can be used to show subtle changes in material characteristics and determine cumulative (total) permeation when acceptable 'dose' levels of the test chemical can be determined. On the other hand some material-chemical systems take a long time to reach steady-state or exceed the capacity of the detector. In addition, the lack of widespread data on acceptable dermal exposure levels for most chemicals leads many specifiers to rely on breakthrough times exclusively.

The majority of permeation tests in the protective clothing industry are conducted using neat chemical continuously contacting pristine material at room temperature for a period of eight hours. General testing on common chemicals, such as those listed in ASTM F 1001 and ISO 6529, are generally performed for comparing material permeation performance (see chemicals listed in Table 12.14). Test sensitivities are at 0.10 μg/cm^{2}min or better but may be higher for difficult-to-evaluate chemicals. Other barrier materials are generally evaluated against chemicals for longer periods of time at slightly elevated temperatures for examining steady state permeation rates and cumulative permeation. These test conditions are considered worst case, because constant contact of the material with the chemical is maintained which may or may not be representative of actual use. When specific barrier product applications are identified, it is best to model the conditions of use through the selection of test parameters. If general performance is to be determined, using industry practices for test set up are preferred so that material performance may be compared against other available data.

12.5 Overall CPC integrity performance

Product integrity refers to the ability of entire clothing systems to prevent inward leakage of chemicals, whether in gaseous, liquid, or particulate forms. Tests for measuring product integrity complement material barrier tests because the clothing design has a significant effect on the overall protection to the end user. A material with good barrier characteristics against chemical vapors in clothing with a poor design (in terms of vapor or gas-tight integrity) will still result in exposure. Thus, product integrity tests evaluate the other parts of clothing such as:

Table 12.13 Comparison of penetration and permeation resistance for representative liquid splash-protective barrier materials

Chemical	PVC/nylon			Saranex/Tyvek laminate			Microporous film/nonwoven laminate		
	F903(C) Result[a]	F739 B.T.[b]	F739 P.R.[c]	F903(C) Result	F739 B.T.	F739 P.R.	F903(C) Result	F739 B.T.	F739 P.R.
Acetone	Pass	8	>50	Pass	28	3.4	Pass	<4	>50
Acetonitrile	Pass	12	25	Pass	88	0.27	Pass	<4	>50
Carbon disulfide	Fail (6)	4	>50	Pass	4	>50	Pass	<4	>50
Dichloromethane	Fail (6)	4	>50	Pass	4	>50	Pass	<4	>50
Diethylamine	Fail (20)	8	>50	Pass	20	20	Pass	<4	>50
Dimethylformamide	Fail (40)	28	>50	Pass	72	1.8	Pass	<4	>50
Ethyl acetate	Pass	8	>50	Pass	20	1.5	Pass	<4	>50
Hexane	Fail (40)	20	8	Pass	None	N/A	Pass	<4	>50
Methanol	Fail (55)	16	13	Pass	None	N/A	Pass	<4	>50
Nitrobenzene	Pass	32	>50	Pass	120	6.0	Pass	<4	>50
Sodium hydroxide	Pass	None	N/A	Pass	None	N/A	Pass	<4	>50
Sulfuric acid	Pass	120	6	Pass	None	N/A	Pass	<4	>50
Tetrachloroethylene	Fail (30)	16	>50	Pass	128	1.3	Pass	<4	>50
Tetrahydrofuran	Pass	8	>50	Pass	4	>50	Pass	<4	>50
Toluene	Fail (25)	12	>50	Pass	24	40	Pass	<4	>50

Abbreviations: B.T. – breakthrough time in minutes, P. R. – permeation rate in ìg/cm^{2}min, N/A – not applicable. *Source*: ref. 16.
Penetration results provide a pass or fail with penetration in parentheses; permeation tests per ASTM F739 at ambient temperature for three hours.

Table 12.14 ASTM F 1001 chemicals and key properties

Chemical	Class	Molecular weight	Vapor pressure (mm Hg)	Molar volume (cm^3/mol)	Specific gravity
Acetone	Ketone	58	266	74.0	0.791
Acetonitrile	Nitrile	41	73	53.0	0.787
Ammonia	Inorganic gas	17	>760	—	N/A
1,3-Butadiene	Alkene	54	910	87.0	N/A
Carbon disulfide	Sulfur compound	76	300	62.0	1.260
Chlorine	Inorganic gas	70	> 760	—	N/A
Dichloromethane	Halogen compound	85	350	63.9	1.336
Dimethylformamide	Amide	73	2.7	77.0	0.949
Ethyl acetate	Ester	88	76	99.0	0.920
Ethylene oxide	Heterocyclic	44	>760	—	N/A
Hexane	Aliphatic	86	124	131.6	0.659
Hydrogen chloride	Inorganic gas	37	>760	—	N/A
Methanol	Alcohol	32	97	41.0	1.329
Methyl chloride	Halogen compound	51	>760	—	N/A
Nitrobenzene	Nitro compound	123	$\ll1$	102.7	1.203
Sodium hydroxide	Inorganic base	40	0	N/A	2.130
Sulfuric acid	Inorganic acid	98	<0.001	N/A	1.841
Tetrachloroethylene	Halogen compound	166	14	101.1	1.631
Tetrahydrofuran	Ether	72	145	81.7	0.888
Toluene	Aromatic	92	22	106.8	0.866

- seams
- closures
- interfaces with other clothing (such as sleeve ends with gloves and trouser cuffs with footwear)
- interfaces with other equipment (such as with a respirator).

As with material chemical resistance, there are three principal types of overall product integrity testing:

1. particulate-tight integrity
2. liquid-tight integrity
3. gas-tight integrity.

12.5.1 Particulate-tight integrity

Particle-tight integrity tests determine if particles enter whole items of CPC. In this testing, protective clothing samples are either placed on a manikin or worn by a test subject. The manikin or test subject is then exposed to a particulate atmosphere, usually an aerosol formed by a non-toxic, easily detectable liquid. Human subjects usually perform a series of exercises to put stress on the garment. The particulate-contaminated atmosphere and atmosphere inside the protective clothing are sampled either to determine the levels of particle intrusion inside the protective clothing, or measure rates of particle release from the protective clothing when worn inside a 'clean' chamber.

A number of informal test methods have been established in the United States that use corn oil or other aerosols in a chamber to measure intrusion into the PPE by sampling air. In Europe and internationally, ISO 13982-2 has been adopted as a test method, which uses a sodium chloride aerosol that is introduced into a chamber with a test subject wearing the protective clothing to be evaluated. Sampling of air to determine salt concentration both inside and outside the clothing is used to determine clothing effectiveness against particles. Garment performance is usually characterized in terms of 'intrusion coefficient' which is the ratio of the outside contaminant concentration to the concentration of contaminant measured on the inside. Higher intrusion coefficients indicate garments with better resistance to penetration by particles.

12.5.2 Liquid-tight integrity

Liquid integrity tests determine if liquid enters to the interior side of the CPC or onto wearer underclothing. Methods for measuring liquid-tight integrity involve spraying protective clothing on a manikin with a liquid and observing penetration of liquid onto an inner liquid absorptive garment or the interior of the clothing. Water is often treated with either surfactant to lower surface tension and to better simulate organic liquids, and/or dyes to enhance detection of penetrating liquid. In general, tests may be conducted at periods longer than expected exposure to assist in observing leakage. Several techniques can be used to quantify leakage such as in the use of spectrophometry on dye-based liquid challenges and electroconductivity for salt-based liquid challenges. However, the majority of testing is performed with visual detection of liquid leakage. Most results are therefore reported as detected penetration in terms of passing or failing performance. Observations of areas where leakage occurred may also be reported to help determine problems in the product that limit the clothing item's integrity. Table 12.15 provides a comparison of these methods.

The available test methods provide slightly different test approaches for measuring liquid-tight integrity:

- ASTM F 1359 involves placing clothing on a manikin and spraying the manikin with surfactant-treated water from five different nozzles. The volumetric flow out of each nozzle is specified. In various applications of this test method, the liquid is sprayed at the manikin from 4 minutes to one hour. During the exposure period, the manikin is rotated through four orientations to completely challenge the garment. An inner liquid-absorptive garment worn on the manikin underneath the clothing is used for detecting liquid penetration. The garment interior can also be examined. Test results are recorded as 'pass' or 'fail'.
- EN 468 is similar to ASTM F 1359, in that it involves surfactant treated water that is sprayed at the protective clothing in a specified pattern over a specified duration. However, this test involves a human test subject (who wears a liquid-absorptive garment and performs a series of exercises) and requires the use of a dye. Performance of the garment is determined by measuring the total area of dye staining on the liquid-absorptive garment and relating that area to the area of a 'calibrated' stain representing a specific volume of penetrating liquid.
- In EN 463, an aqueous jet, containing a fluorescent or visible dye tracer, is directed under controlled conditions at chemical protective clothing worn by a test manikin or human test subject. Inspection of the inside surface of the clothing and the outside surface of absorbent clothing worn underneath allows any points of inward leakage to be identified.

ISO 17491 covers all three approaches and provides criteria for applying each test:

- Method C specifies a method for determining the resistance of chemical protective clothing to penetration by jets of liquid chemicals (analogous to EN 463). This procedure is applicable to clothing which may comprise one or more items and which is intended to be worn where there is a risk of exposure to a forceful projection of a liquid chemical. It is also applicable to clothing which is intended to be resistant to penetration under conditions which

Table 12.15 Characteristics of liquid-tight integrity tests for complete chemical protective clothing

Test method	Clothing placement	Test liquid	Liquid application	Method of detection
ASTM F 1359 (also ISO 17491, Procedure E)	Clothing placed on manikin that is dressed in liquid-absorptive garment	Water treated with surfactant to 32 dynes/cm	Liquid sprayed from 5 nozzles positioned above and to sides of test clothing at 3.0 L/min from each nozzle for 60 minutes; manikin is rotated through 4 positions during test	Interior of garment and liquid-absorptive garment is examined for signs of liquid penetration; results are pass/fail
EN 463 (also ISO 17491, Procedure C)	Human subject wears test clothing over liquid-absorptive garment; alternatively clothing may be placed on manikin	Water treated with fluorescent dye	Liquid directed at specific locations on test clothing at pressure of 180 kPa at distance of 1 m for 5 seconds; if human subject is used, subject remains stationary	Staining of liquid-absorptive garment is compared with calibrated stain (0.1 ml); approximate area of staining is reported
EN 468 (also ISO 17491, Procedure D)	Human subject wears test clothing over liquid-absorptive garment; subject stands on turntable	Water treated with surfactant to 30 dynes/cm and fluorescent dye	Liquid sprayed from 4 nozzles positioned vertically on test stand beside test subject (at distance of 1.5 m); liquid is sprayed at 1.14 L/min from each nozzle for 1 minute; during spray, subject performs stationary exercises	Staining of liquid-absorptive garment is compared with calibrated stain (0.1 ml); approximate area of staining is reported
ISO 17491 Procedure F	Human subject wears test clothing over liquid-absorptive garment; subject stands on turn-table	Water treated with surfactant to 52.5 dynes/cm an fluorescent dye	Same as EN 468 (or Procedure D of ISO 17941) except that flow rate is at 0.47 L/min	Staining of liquid-absorptive garment is compared with calibrated stain (0.1 ml); approximate area of staining is reported

require total body surface cover but do not demand the wearing of gas-tight clothing.

- Method D specifies a method for determining the resistance of chemical protective clothing to penetration by sprays of liquid chemicals (based on EN 468). This procedure applies to protective clothing which may comprise one or more items and which is intended to be worn when there is a risk of exposure to slight splashes of a liquid chemical or to spray particles that coalesce and run off the surface of the garment.
- Method E specifies an alternative method for determining the resistance of chemical protective clothing to penetration by sprays of liquid chemicals (based on ASTM F 1359). This procedure applies to protective clothing which may comprise one or more items and which is intended to be worn when there is a risk of exposure to slight splashes of a liquid chemical or to spray particles that coalesce and run off the surface of the garment.
- Method F is a modification of Method D where the spray has been modified to light spray or mist by use of different nozzles and spray conditions. This method is intended for partial body protective clothing where the likelihood of splash exposure is low.

12.5.3 Gas-tight integrity

Gas-tight integrity tests determine if gas or vapor can penetrate protective clothing. Gas-tight integrity testing can only be performed on items that can be sealed, including totally encapsulating suits. The most common approach for testing gas-tight integrity of protective clothing is to inflate the item to a specified pressure and then observe for any change in pressure within the item after several minutes. Using a soapy water solution on exterior of the clothing can then identify the location of leaks. Alternative approaches involve placing PPE on a test subject in closed environment containing a gas (such as ammonia) and measuring concentration of challenge agent inside suit. In some rare cases, full-scale testing of suits against actual hazardous materials has been performed in special projects.

Both ASTM F 1052 and EN 464 involve similar testing approaches where the protective clothing is inflated and left at a specific pressure. ASTM F 1052 uses a lower test pressure than EN 464, but the results are similar. Extensive work by Carroll[38] has demonstrated that a test pressure of 1 kPa over a four-minute period is sensitive enough to evaluate most encapsulating clothing for very small leaks that could contribute to poor integrity. ISO 17491 involves a challenge environment where a test subject wears the clothing inside a closed chamber in contact with a test agent. The subject performs a series of exercises while wearing the clothing. The interior of the clothing is either measured during or after the exposure to determine the ratio of the concentration on the outside to the ratio of the concentration of test agent on the inside. This ratio, known as the intrusion coefficient, is used to measure clothing performance similar to the way protection factors are used to judge the performance of respirators.

12.6 Other CPC performance properties

A number of other methods for evaluating CPC garments and materials are often needed for assessing performance properties other than chemical resistance and integrity. These properties relate to material physical properties and ergonomic properties.

12.6.1 CPC material physical properties

A number of other properties are important for judging the effective of chemical protective clothing selections. Physical properties assess or determine:

- weight and thickness of clothing and materials
- strength of clothing
- resistance to specific physical hazards
- product durability.

In general, more than one test method may be available for a performance property based on the type of material or product. In addition, many material physical property results are reported in different material directions. Results that are parallel to the direction the material is fabricated or comes off the roll are referred to as warp direction for woven textile fabrics, course direction for knit textile fabrics, and machine direction for nonwoven textile, rubber, and plastic materials. Results that are perpendicular to the direction the material is fabricated or comes off the roll are referred to as the fill or weft direction for woven textile fabrics, wales or weft direction for knit textile fabrics, and cross-machine direction for nonwoven textile, rubber, and plastic materials.

The multitude of different physical properties prevents detailed coverage of this performance area in this chapter. Typical physical properties applied to chemical protective clothing include:

- Weight is reported as the weight of a material per unit area.
- Thickness is reported as the nominal or average thickness of a material in mils (thousands of an inch) or millimeters.
- Breaking strength measures the force required to break clothing materials or components when items are pulled along one direction; breaking strength tests can also be used to measure the strength of seams and closures.
- Burst strength measures the force or pressure required to rupture clothing materials or components when a force is directed perpendicular to the item; this property may be related to ability of PPE materials to prevent items from protruding through garments.

- Tear or snag resistance measures the force required to continue a tear in a clothing material once initiated or the resistance of a material in preventing a tear or snag from occurring.
- Abrasion resistance measures the ability of clothing surfaces or materials to resist wearing away when rubbed against other surfaces.
- Cut resistance measures the ability of clothing items or materials to resist cutting through by a sharp-edged objects or machinery.
- Puncture resistance measures the ability of clothing items or materials to resist penetration by a slow-moving, pointed object.
- Flex fatigue resistance measures the ability of clothing items or materials to resist wear or other damage when repeatedly flexed.
- Flame resistance determines if material will ignite and continue to burn after exposed to flame.

Table 12.16 provides representative test methods for many of the above listed physical properties. For each physical property reviewed, it is important to understand how the test method related to the intended use of the protective clothing and how to interpret the measurement. For some properties, increasing values generally mean better performance. But physical properties that are too

Table 12.16 List of representative physical performance test methods

Physical property	Type of test/material application	Available test methods
Weight	Woven and knit textiles	ASTM D 3776 ISO 3801
	Nonwoven textiles	ASTM D 1117 ISO 9073-1
	Coated fabrics	ASTM D 751 ISO 2286
Thickness	Woven and knit textiles	ASTM D 1777 ISO 5084
	Nonwoven textiles	ASTM D 5736 ISO 9073-2
	Coated fabrics	ASTM D 751 ISO 2286
Breaking strength	Grab method – textiles	ASTM D 5034 EN ISO 13934-2
	Strip method – textiles	ASTM D 5035 EN ISO 13934-1
	Nonwoven textiles	ISO 9073-3
	Rubber/coated fabrics	ASTM D 412 ASTM D 751 ISO 1421
	Plastic	ASTM D 638 ASTM D 882 ISO 1421

Table 12.16 Continued

Physical property	Type of test/material application	Available test methods
	Seam strength	ASTM D 751 ASTM D 1683 EN ISO 13934-1
Burst strength	Ball method – textiles	ASTM D 3787 ASTM D 3940
	Ball method – rubber or plastic	ISO 3303
	Diaphragm method – textiles	ASTM D 3786
	Diaphragm method – rubber or plastic	ISO 2960
	Coated fabrics	ASTM D 751
Tear resistance	Elmendorf method – textiles	ASTM D 1424 ISO 13937
	Elmendorf method – plastics	ASTM D 1922
	Tongue tear – textiles	ASTM D 2261 ISO 13937
	Tongue tear – nonwoven textiles	ASTM D 5735
	Tongue tear – plastics	ASTM D 1938
	Trapezoidal method – textiles	ASTM D 5733 ISO 9073-4
	Tear resistance – plastics	ASTM D 1004 ISO 4674
	Tear resistance – coated fabrics, rubber	ASTM D 751 ISO 4676
	Puncture propagation tear resistance	ASTM D 2582 ISO 13995
Abrasion resistance	Taber method – textiles	ASTM D 3884
	Taber method – coated fabrics	ASTM D 3389 ISO 5470-1
	Taber method – plastics	ASTM D 1044
	Wyzenbeek method – textiles	ASTM D 4157
	Martindale method – clothing materials	ASTM D 4966 EN 530 ISO 12974
	Flexing/abrading method – textiles	ASTM D 3885
	Flexing/abrading method – coated fabrics	ISO 5981
	Inflated diaphragm method – textiles	ASTM D 3886
	Uniform method – textiles	ASTM D 4158
Cut resistance	Clothing materials	ASTM F 1790 ISO 13997
Puncture resistance	Clothing materials	ASTM F 1342 EN 863 ISO 13996
Flex fatigue	Flat material	ASTM F 392 ISO 7854
Flammability	Clothing materials	ASTM F 1358 EN 532 ISO 15025

ASTM – American Society for Testing and Materials; EN – European Norm; ISO – International Standards Organization.

high may also create a tradeoff for such properties as stiffness or aspects of clothing related to use.

12.6.2 CPC ergonomic properties

Ergonomic properties describe how CPC affects the wearer in terms of functionality, fit, comfort, and overall well-being. Most ergonomic properties represent tradeoffs with protection, for example, barriers to chemicals versus thermal comfort. Common ergonomic properties for CPC include:

- Material compatibility evaluates the potential for skin irritation or adverse reactions due to contact with certain substances which may be present in or on clothing.
- Thermal insulation and breathability evaluate the ability of CPC materials to allow the passage of air, moisture, and the heat associated with body evaporative cooling and environmental conditions.
- Mobility and range of motion evaluate the effects of CPC on wearer function in performing work tasks.
- Clarity and field of vision evaluate the ability of an individual to see through a visor or a faceshield; field of vision testing evaluates peripheral vision for an individual wearing the visor or faceshield.
- Ease of communication evaluates the ability of CPC to allow intelligible (understood) communication of the wearer with other persons.
- Sizing and fit determines how well clothing fits the individual wearer.
- Donning and doffing ease evaluates how easily or how quickly individuals can put on and take off protective clothing.

Most ergonomic properties are difficult to measure and must employ human subjects. For this reason, most human-factor evaluations are conducted as wear trials where end users can rate or rank different properties related to function and comfort for different clothing items. In some cases, standardized test methods exist for measuring human factors. Representative standard test methods for ergonomic properties described in this subsection are summarized in Table 12.17.

12.7 CPC specification and classification standards

A number of overall standard specifications or classifications for CPC have been developed. Specifications generally establish minimum performance criteria while classifications provide a means for ranking products based on standard test methods. In the United States, the primary protective clothing standards that have been developed are related to emergency response applications. These include NFPA 1991 and NFPA 1992. Both standards cover ensemble that are the combination of suits or garments, with gloves and footwear for complete body protection. Performance criteria are provided in terms of:

Table 12.17 List of representative human factors test methods

Human factor	Type of test/application	Available test methods
Material biocompatibility	Medical device (gloves, gowns) biocompatibility tests	ISO 10993
	Natural rubber latex proteins	ASTM D 5712
Thermal insulation and breathability	Air permeability – materials	ASTM D 737 ISO 9237
	Moisture vapor transmission – materials	ASTM E 96 CAN/CGSB-4.2 No. 49 ISO 15106
	Thermal resistance – materials	ASTM D 1518 ISO 5085
	Thermal resistance – garments	ASTM F 1291
	Total heat loss – materials	ASTM F 1868 ISO 11092
Mobility and range of motion	Overall product evaluation	ASTM F 1154 NFPA 1991, Section 8.4 EN 943-1, Clause 7.2
Clarity and field of vision	Clarity/field of vision	NFPA 1991, Section 8.4 EN 943-1, Clause 7.2
	Haze and transmittance	ASTM D 1003 ISO 14782
Sizing and fit	Garment sizing/dynamic fit test	ASTM F 1731 ANSI/ISEA 101 EN 340 ISO 13688
Donning and doffing ease	Full body suits	NFPA 1991, Section 8.4

ANSI – American National Standards Institute; ASTM – American Society for Testing and Materials; EN – European Norm; CAN/CGSB – Canadian General Standards Board; ISO – International Standards Organization; NFPA – National Fire Protection Association.

- overall ensemble integrity
- material chemical resistance
- material flame resistance
- material physical properties
- clothing human factors
- component function (e.g., airline pass-throughs for respiratory equipment and exhaust valves).

Two different levels are established by these standards based on overall ensemble integrity and material chemical resistance. This scheme associated clothing gas-tight integrity and material permeation resistance with vapor protection and clothing liquid-tight integrity, and material penetration resistance with liquid splash protection. Using this hierarchy, the NFPA attempted to define protective clothing types on the basis of needed performance as demonstrated by test methods designed to measure the type of protection provided. In addition to performance criteria, these standards establish requirements for third-party certification and labeling of suits and clothing for demonstrating compliance with these standards. Manufacturers must also meet certain design criteria and provide documentation to the end user such as instructions and technical data supporting claims against the standard.

In Europe, several standards have been developed related to chemical protective clothing and equipment. These include:

- EN 465 (Type 4: spray-tight chemical protective clothing)
- EN 466 (Type 3: liquid-tight chemical protective clothing)
- EN 467 (partial body chemical protective clothing)
- EN 943-1 (Types 1 and 2: gas-tight chemical protective clothing)
- EN 943-2 (Type 1-ET: gas-tight chemical protective clothing for emergency teams)
- prEN 13034 (Type 6: chemical protective clothing with limited liquid protection)
- EN 13982-2 (Type 5: particulate-tight chemical protective clothing)
- prEN 14605 (Type 3, 4, and partial body chemical protective clothing) to replace EN 465, 466, and 467.

Each standard defines a specific type of chemical protective clothing with differences in the intended protection, based on general clothing design, clothing integrity and the type of chemical resistance provided. In each of the standards (with the exception of EN 943-2), clothing performance is classified in terms of material performance for chemical resistance, physical properties, and other properties. Each standard also specifies certain minimum design and integrity performance for the respective type of clothing.

Under the International Standards Organization, an effort to harmonize requirements for chemical protective clothing between Europe and North American has resulted in a proposed standard, ISO 16602. In essence, this standard consolidates many of the clothing types and performance classifications into one standard.

12.8 Summary

A wide variety of clothing and equipment is available in the workplace for industrial chemical protection. These items can be ‘type’ classified by their general design, performance, and service life. Specific details related to the choice of materials, design features, construction methods, and performance features further serve to differentiate among the type of chemical protective clothing. An understanding of performance tests affecting both materials and the overall product are especially important for determining the appropriateness of different CPC items for specific applications.

12.9 References

1. Stull J O, 'Selecting chemical protective clothing,' *Occup Health & Safety*, December 1995, 20–24.
2. Bray A R and Stull J O, 'A new nondestructive inspection method to determine fatigue in chemical protective suit and shelter materials,' *Performance of Protective Clothing: Fifth Volume, ASTM STP 1237* (J S Johnson and S Z Mansdorf, eds.), American Society for Testing and Materials, Philadelphia, 1996, 281–95.
3. Dudzinski D J, 'Kennedy space center maintenance program for propellant handlers ensembles,' *Performance of Protective Clothing: Second Symposium, ASTM STP 989* (S Z Mansdorf, R G Sager, and A P Nielson, eds.), American Society for Testing and Materials, Philadelphia, PA, 1988, 492–500.
4. Garland C E and Torrence A M, 'Protective clothing materials: Chemical contamination and decontamination concerns and possible solutions,' *Performance of Protective Clothing: Second Symposium, ASTM STP 989* (S Z Mansdorf, R G Sager, and A P Nielson, eds.), American Society for Testing and Materials, Philadelphia, PA, 1988, 368–75.
5. Schwope A D and Renard E, 'Estimation of the cost of using chemical protective clothing,' *Performance of Protective Clothing: Fourth Volume, ASTM STP 1133*, J P McBriarty and N W Henry, eds., ASTM, Philadelphia, 1992, 972–81.
6. Fraser A J and Keeble V B, 'Factors influencing design of protective clothing for pesticide application,' *Performance of Protective Clothing: Second Symposium, ASTM STP 989* (S Z Mansdorf, R G Sager, and A P Nielson, eds.), American Society for Testing and Materials, Philadelphia, PA, 1988, 565–72.
7. Baars D M, Eagles D B and Edmond J A, 'Test method for evaluating adsorptive Fabrics,' *Performance of Protective Clothing, ASTM STP 900* (R L Barker and G C Coletta, eds.), American Society for Testing and Materials, Philadelphia, PA, 1986, 39–50.
8. Keeble V B, Prevatt M B and Mellian S A, 'An evaluation of fit of protective coveralls manufactured to a proposed revision of ANSI/ISEA 101,' *Performance of Protective Clothing: Fourth Volume, ASTM STP 1133* (J P McBriarity and N W Henry, eds.), American Society for Testing and Materials, Philadelphia, 1992, 675–90.
9. Stull J O, 'Performance standards and testing of chemical protective clothing,' *Proceedings for Clemson University's Sixth Annual Conference on Protective Clothing*, Greenville, South Carolina, 1992.
10. Coletta G C, Mansdorf S Z and Berardinelli S P, 'Chemical protective clothing standard test method development: Part II. Degradation test method,' *Am Ind Hyg Assoc J, 1988,* **49,** 26–33.
11. Schwope A D, Carroll T R. Haung R and Royer M D, 'Test kit for evaluation of the chemical resistance of protective clothing,' *Performance of Protective Clothing: Second Symposium, ASTM STP 989* (S Z Mansdorf, R Sager, and A P Nielsen, eds.), American Society for Testing and Materials, Philadelphia, 1988, p. 314–30.
12. Stull J O, 'Early development of a hazardous chemical protective ensemble,' Final Report CG-D-24-86, AD A174, 885, Washington, D.C., 1986.
13. Van Amerongen G J, 'Diffusion in elastomers,' *Rubber Chem Technol,* 1964*,* **37**, 1065–81.
14. Mansdorf S Z and Berardinelli S P, 'Chemical protective clothing standard test method development, Part 1. Penetration method,' *Am Ind Hyg Assoc J*, 1988, **49**, 21–5.

15. Berardinelli S P and Cottingham L, 'Evaluation of chemical protective garment seams and closures for resistance to liquid penetration,' *Performance of Protective Clothing, ASTM STP 900* (R L Barker and G C Coletta, eds.), American Society for Testing and Materials, Philadelphia, 1986, 263–75.
16. Stull J O, White D F and Greimel T C., 'A comparison of the liquid penetration test with other chemical resistance tests and its application in determining the performance of protective clothing,' *Performance of Protective Clothing: Fourth Volume*, ASTM STP 1133 (J P McBriarity and N W Henry, eds.), American Society for Testing and Materials, Philadelphia, 1992, pp. 123–38.
17. Stull J O., 'Performance standards for improving chemical protective suits,' *Chemical Protective Clothing Performance in Chemical Emergency Response, ASTM STP 1037* (J L Perkins and J O Stull, eds.), American Society for Testing and Materials, Philadelphia, 1989, 245–64.
18. Henry N W and Schlatter C N, 'The development of a standard method for evaluating chemical protective clothing to permeation by liquids,' *Am Ind Hyg Assoc J*, 1981, **42**, 202–7.
19. Stull J O and Pinette, M F S, 'Special considerations for conducting permeation testing of protective clothing materials with gases and chemical vapors,' *Am Ind Hyg Assoc J*, 1900, **51**, 378–85.
20. Stull J O, Pinette M F S, and Green R, 'Permeation of ethylene oxide through protective clothing materials for chemical emergency response,' *App Ind Hyg*, 1990, **5** 448–62.
21. Lara J and Drolet D, 'Testing the resistance of protective clothing materials to nitroglycerin and ethylene glycol dinitrate,' *Performance of Protective Clothing: Fourth Volume, ASTM STP 1133* (J P McBriarity and N W Henry, eds.), American Society for Testing and Materials, Philadelphia, 1992, pp. 153–61.
22. Schwope, A D, Goydan R, Carroll T R, and Royer, M D, 'Test methods development for assessing the barrier effectiveness of protective clothing materials,' Proceedings of the Third Scandinavian Symposium on Protective Clothing Against Chemicals and Other Heath Risks, Norwegian Defence Research Establishment, Gausdal, Norway, September 1989.
23. Man, V L, Bastecki V, Vandal G, and Bentz A P, 'Permeation of protective clothing materials: Comparison of liquid contact, liquid splashes, and vapors on breakthrough times,' *Am Ind Hyg Assoc J*, 1987, **48**, 551–62.
24. Pinette M F S, Stull J O, Dodgen C R, and Morley M G, 'A new permeation testing collection method for non-volatile, non-water soluble chemical challenges of protective clothing,' *Performance of Protective Clothing: Fourth Volume, ASTM STP 1133* (J P McBriarity and N W Henry, eds.), American Society for Testing and Materials, Philadelphia, 1992, 339–49.
25. Ehntholt D J, Cerundolo D L, Dodek I, Schwope A D, Royer M D, and Nielsen A P, 'A test method for the evaluation of protective glove materials used in agricultural pesticide operations,' *Am Ind Hyg Assoc J*, 1990 **51**, 462–68.
26. Swearengen P M, Johnson J S, and Priante S, 'A modified method for fabric permeation testing,' Paper presented at 1991 Am Ind Hyg Conf, Salt Lake City, Utah, 1991.
27. Spence M W, 'Chemical permeation through protective clothing materials: An evaluation of several critical variables,' Presented at Am. Ind. Hyg. Conference, Portland, Oregon, 1981.
28. Bentz A P and Man V L, 'Critical variables regarding permeability of materials for

totally encapsulating suits,' Proceedings of the 1st Scandinavian symposium on protective clothing against chemicals, Copenhagen, Denmark, 1984.

29. Nelson G O, Lum B Y, and Carlson G J, 'Glove permeation by organic solvents,' *Am Ind Hyg Assoc J*, 1981, **42**, 217–24.
30. Huang R Y and Lin V J C, *J App Polymer Sci*, 1968, **12**, 2615–23.
31. Vahdat N and Bush M, 'Influence of temperature on the permeation properties of protective clothing materials,' *Chemical Protective Clothing Performance in Chemical Emergency Response, ASTM STP 1037*, (J L Perkins and J O Stull, eds.), American Society for Testing and Materials, Philadelphia, 1989, 132–45.
32. Stampher J F, McLeod M J, Bettis M R, Martinez A M, and Berardinelli S P, 'Permeation of polychlorinated biphenyls and solutions of these substances through selected protective clothing materials,' *Am Ind Hyg Assoc J*, 1984, **45**, 634–41.
33. Schwope A D, Goydan R, Ehntholt D J, Frank U, and Nielsen A P, 'Permeation resistance of glove materials to agricultural pesticides,' *Performance of Protective Clothing: Fourth Volume, ASTM STP 1133* (J P McBriarity and N W Henry, eds.), American Society for Testing and Materials, Philadelphia, 1992, 198–209.
34. Mickelsen R L, Roder M M, and Berardinelli S P, 'Permeation of chemical protective clothing by three binary solvent mixtures,' *Am Ind Hyg Assoc J*, 1986, **47**, 236–40.
35. Ridge M C and Perkins J L, 'Permeation of Solvent mixtures through protective clothing elastomers,' *Chemical Protective Clothing Performance in Chemical Emergency Response, ASTM STP 1037* (J L Perkins and J O Stull, eds.), American Society for Testing and Materials, Philadelphia, 1989, 113–31.
36. Goydan R, Powell J R, Bentz A P, and Billing C B, 'A computer system to predict chemical permeation through fluoropolymer-based protective clothing,' *Performance of Protective Clothing: Fourth Volume, ASTM STP 1133* (J P McBriarity and N W Henry, eds.), American Society for Testing and Materials, Philadelphia, 1992, 956–71.
37. Jamke R A, 'Understanding and using chemical permeation data in the selection of chemical protective clothing,' *Chemical Protective Clothing Performance in Chemical Emergency Response, ASTM STP 1037* (J L Perkins and J O Stull, eds.), American Society for Testing and Materials, Philadelphia, 1989, 11–22.
38. Carroll T R, Resha C J, Vencill C T, and Langley J D, 'Determining the sensitivity of international test methods design to assess the gas-tight integrity of fully encapsulating garments,' *Performance of Protective Clothing, Sixth Volume*, ASTM STP 1273 (J O Stull and A D Schwope, eds.), American Society for Testing and Materials, 1997, 3–15.

12.10 Appendix: list of referenced standards

American Association of Textile Chemist and Colorist (AATCC) Test Methods

AATCC 42, Water resistance: Impact penetration test.
AATCC 127, Water resistance: Hydrostatic pressure test.

American Society for Testing and Materials (ASTM)

ASTM D 412, Test methods for vulcanized Rubber and thermoplastic rubbers and thermoplastic elastomers – Tension.

ASTM D 471, Test method for rubber property – Effect of liquids.

ASTM D 543, Practices for evaluating the resistance of plastics to chemical reagents.

ASTM D 638, Test method for tensile properties of plastics.

ASTM D 737, Test method for air permeability of textile fabrics.

ASTM D 751, Methods for testing coated fabrics.

ASTM D 882, Test methods for tensile properties of thin plastic sheeting.

ASTM D 1003, Standard test method for haze and luminous transmittance of transparent plastics.

ASTM D 1004, Test method for initial tear resistance of plastic film and sheeting.

ASTM D 1044, Test Method for resistance of transparent Plastics to surface abrasion.

ASTM D 1117, Methods of testing nonwoven fabrics.

ASTM D 1242, Test methods for resistance of plastic materials to abrasion.

ASTM D 1424, Test method for tear resistance of woven fabrics by falling pendulum (Elmendorf) apparatus.

ASTM D 1518, Test method for thermal transmittance of textile material.

ASTM D 1683, Test method for failure in sewn seams of woven fabrics.

ASTM D 1777, Method for measuring thickness of textile materials.

ASTM D 1922, Test method for propagation tear resistance of plastic film and thin sheeting by pendulum method.

ASTM D 1938, Test method for tear propagation resistance of plastic film and thin sheeting by a single-tear method.

ASTM D 2261, Test method for tearing strength of woven fabrics by the tongue (single rip) method (constant-rate-of-extension tensile testing machine).

ASTM D 2582, Test method for puncture-propagation tear resistance of plastic film and thin sheeting.

ASTM D 3776, Test methods for mass per unit area (weight) of woven fabric.

ASTM D 3786, Test method for hydraulic bursting strength of knitted goods and nonwoven fabrics: Diaphragm bursting strength tester method.

ASTM D 3787, Test method for bursting strength of knitted goods: Constant-rate-of traverse (CRT), ball burst test.

ASTM D 3884, Test method for abrasion resistance of textile fabrics (rotary platform, double-head method).

ASTM D 3885, Test method for abrasion resistance of textile fabrics (flexing and abrasion method).

ASTM D 3886, Test method for abrasion resistance of textile fabrics (inflated diaphragm method).

ASTM D 3940, Test method for bursting strength (load) and elongation of sewn seams of knit or woven stretch textile fabrics.

ASTM D 4157, Test method for abrasion resistance of textile fabrics (oscillatory cylinder method).

ASTM D 4158, Test method for abrasion resistance of textile fabrics (uniform abrasion method).

ASTM D 4966, Test Method for abrasion resistance of textile fabrics (martindale abrasion tester method).

ASTM D 5034, Test method for breaking force and elongation of textile fabrics (grab test).

ASTM D 5035, Test method for breaking force and elongation of textile fabrics (strip test).

ASTM D 5712, Test method for analysis of proteins in natural rubber and its products.

ASTM D 5733, Test method for tearing strength of nonwoven fabrics by the trapezoid procedure.

ASTM D 5735, Test method for tearing strength of nonwoven fabrics by the tongue (single rip) procedure (constant-rate-of-extension tensile testing machine).

ASTM D 5736, Test method for thickness of highloft nonwoven fabrics.

ASTM E 96, Test methods for water vapor transmission of materials.

ASTM F 392, Test method for flex durability of flexible barrier materials.

ASTM F 739, Test method for resistance of protective clothing materials to permeation by liquids and gases under conditions of continuous contact.

ASTM F 903, Test method for resistance of protective clothing materials to penetration by liquids.

ASTM F 1052, Pressure testing of gas-tight totally encapsulating chemical protective suits.

ASTM F 1154, Practices for qualitatively evaluating the comfort, fit, function, and integrity of chemical protective suit ensembles.

ASTM F 1194, Guide for documenting the results of chemical permeation testing on protective clothing materials.

ASTM F 1291, Test method for measuring the thermal insulation of clothing using a heated manikin.

ASTM F 1342, Test method for protective clothing material resistance to puncture.

ASTM F 1358, Test method for effects of flame impingement on materials used in protective clothing not designated primarily for flame resistance.

ASTM F 1359, Liquid penetration resistance of protective clothing or protective ensembles under a shower spray while on a manikin.

ASTM F 1383, Test method for resistance of protective clothing materials to permeation by liquids and gases under conditions of intermittent contact.

ASTM F 1407, Test method for resistance of chemical protective materials to liquid permeation - permeation cup method.

ASTM F 1731, Practice for body measurements and sizing of fire and rescue services uniforms and other thermal hazard protective clothing.

ASTM F 1790, Test method for measuring cut resistance of materials used in protective clothing.

ASTM F1868, Test method for thermal and evaporative resistance of clothing materials using a sweating hot plate.

ASTM F 2130, Test method for measuring repellency, retention, and penetration of liquid pesticide formulation through protective clothing materials.

Canadian General Standards Board (CGSB)

CAN/CGSB-4.2 No. 49, Resistance of materials to water vapour diffusion.

European Committee on Standardization (CEN)

EN 368, Protective clothing – Protection against liquid chemicals – Test Method: Resistance of materials to penetration by liquids.

EN 369, Protective clothing – Protection against liquid chemicals – Test method: Resistance of materials to permeation by liquids.

EN 340, Protective clothing – General requirements.

EN 463, Protective clothing – Protection against liquid chemicals – Test method: Determination of resistance to penetration by a jet of liquid.

EN 464, Protective clothing – Protection against liquid and gaseous chemicals, including liquid aerosols and solid particles – Test method: Determination of leak-tightness of gas-tight suits.

EN 465, Protective clothing – Protection against liquid chemicals – Performance requirements for chemical protective clothing with spray-tight connections between different parts of the clothing (Type 4 Equipment).

EN 466, Protective clothing – Protection against liquid chemicals – Performance requirements for chemical protective clothing with liquid-tight connections between different parts of the clothing (Type 3 Equipment).

EN 467, Protective clothing – Protection against liquid chemicals – Performance requirements for garments providing chemical protection to parts of the body.

EN 468, Protective clothing – Protection against liquid chemicals – Test method: Determination of resistance to penetration by spray.

EN 530, Abrasion resistance of protective clothing material – Test method.

EN 532, Protective clothing – Protection against heat and flame – Method of test for limited flame spread.

EN 863, Protective clothing – Mechanical properties – Test method: Puncture resistance, 1995.

EN 943-1, Protective clothing against liquid and gaseous chemicals, including aerosols and solid particles – Part 1: Performance requirements for ventilated and non-ventilated 'gas tight' (Type 1) protective clothing and 'non-gas-tight' (Type 2) protective clothing.

EN 943-2, Protective clothing against liquid and gaseous chemicals, including aerosols and solid particles – Part 2: Performance requirements for 'gas tight'

(Type 1) protective clothing for emergency teams (ET).

prEN 13034, Protective clothing against liquid chemicals – Performance requirements for chemical protective suits offering limited protective performance against liquid chemicals (Type 6 equipment).

prEN 14605, Protective clothing against liquid chemicals – Performance requirements for protective clothing.

prEN 14325, Protective clothing against liquid chemicals – Material testing and classification.

International Safety Equipment Association (ISEA)

ANSI/ISEA 101, American National Standard for Limited-Use and Disposable Coveralls – Size and Labeling Requirements.

ANSI/ISEA 105, American National Standard for Hand Protection Selection Criteria.

International Standards Organization (ISO)

ISO 811, Textile fabrics – Determination of resistance to water penetration – Hydrostatic pressure test.

ISO 1420, Rubber- or plastics-coated fabrics – Determination of resistance to penetration by water.

ISO 1421, Fabrics coated with rubber or plastics – Determination of breaking strength and elongation at break.

ISO 2286, Rubber- or plastics-coated fabrics – Determination of roll characteristics.

ISO 2960, Textiles – Determination of bursting strength and bursting distension – Diaphragm method.

ISO 3303, Rubber- or plastics-coated fabrics – Determination of bursting strength.

ISO 3801, Textiles – Woven fabrics – Determination of mass per unit length and mass per unit area.

ISO 4674, Fabrics coated with rubber or plastics – Determination of tear resistance.

ISO 5084, Textiles – Determination of thickness of textiles and textile products.

ISO 5085, Textiles – Determination of thermal resistance Part 2; High thermal resistance.

ISO 5470-1, Rubber- or plastics-coated fabrics – Determination of abrasion resistance – Part 1: Taber abrader.

ISO 5981, Rubber- or plastics-coated fabrics – Determination of flex abrasion.

ISO 6529, Protective Clothing – Protection against chemicals – Determination of resistance of protective clothing materials to permeation by liquids and gases.

ISO 6530, Protective clothing – Protection against liquid chemicals – Determination of resistance of materials to penetration by liquids.

ISO 7854, Rubber- or plastics-coated fabrics – Determination of resistance to damage by flexing, 1995.

ISO 9073-1, Textiles – Test methods for nonwovens – Part 1: Determination of mass per unit area.

ISO 9073-2, Textiles – Test methods for nonwovens – Part 2: Determination of thickness.

ISO 9073-3, Textiles – Test methods for nonwovens – Part 3: Determination of tensile strength and elongation.

ISO 9073-4, Textiles – Test methods for nonwovens – Part 4: Determination of tear resistance.

ISO 9237, Textiles – Determination of the permeability of fabrics to air.

ISO 10993-1, Biological evaluation of medical devices.

ISO 11092, Textiles-Physiological effects – Measurement of thermal and water-vapour resistance under steady-state conditions (sweating guarded-hotplate test).

ISO 12974, Textiles – Determination of abrasion resistance of fabrics by the Martindale method.

ISO 13688, Protective clothing – General requirements.

ISO 13934-1, Textiles – Tensile properties of fabrics – Part 1: Determination of maximum force using the strip method.

ISO 13934-2, Textiles – Tensile properties of fabrics – Part 2: Determination of maximum force using the grab method.

ISO 13937, Textiles – Determination of Resistance to Tear for Woven Fabrics.

ISO 13982-1, Chemical protective clothing – Protection against dust – Part 1: Requirements.

ISO 13982-2, Protective clothing for use against solid particulate chemicals – Part 2: Test method of determination of inward leakage of aerosols of fine particles into suits.

ISO 13994, Clothing for protection against liquid chemicals – Determination of resistance of protective clothing materials to penetration by liquids under pressure.

ISO 13995, Protective clothing – Mechanical properties – Determination of dynamic puncture-tear propagation.

ISO 13996, Protective clothing – Mechanical properties – Determination of resistance to puncture.

ISO 13997, Protective clothing – Mechanical properties – Determination of resistance to cutting by sharp objects.

ISO 14782, Plastics – Determination of haze for transparent materials.

ISO 15025, Clothing for protection against heat and flame – Test methods for limited flame spread materials.

ISO 15106, Plastics – Film and sheeting – Determination of water vapour

transmission rate.

ISO 16602, Clothing for protection against chemicals – Classification and performance requirements (proposed).

ISO 17491, Protective clothing – Protection against gaseous and liquid chemicals – Determination of integrity of protective clothing to penetration by liquids and gases.

ISO 22608, Protective clothing – Protection against liquid chemicals – Measurement of repellency, retention, and penetration of liquid pesticide formulations of protective clothing materials.

National Fire Protection Association (NFPA)

NFPA 1991, Standard on Vapor-Protective Ensembles for Hazardous Chemical Emergencies.

NFPA 1992, Standard on Liquid Splash-Protective Ensembles and Clothing for Hazardous Chemical Emergencies, 1994.