15

Medical textiles

Alistair J Rigby and Subhash C Anand

Faculty of Technology, Bolton Institute, Deane Road, Bolton BL3 5AB, UK

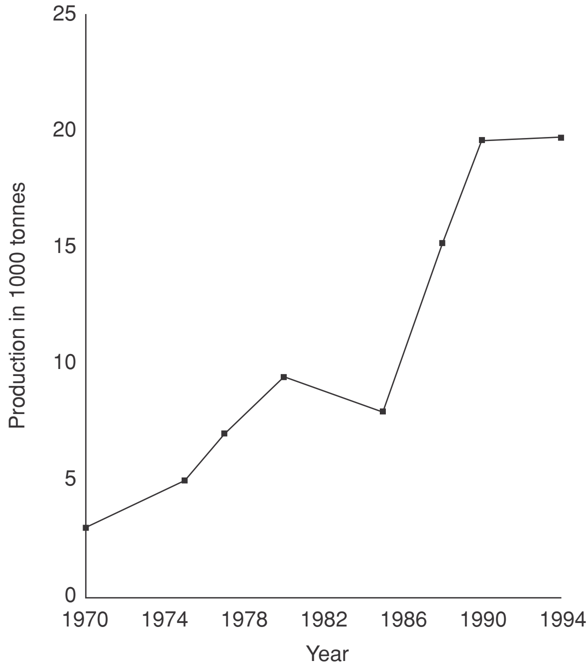
15.1 Introduction

An important and growing part of the textile industry is the medical and related healthcare and hygiene sector. The extent of the growth is due to constant improvements and innovations in both textile technology and medical procedures. The aim of this chapter is to highlight the specific medical and surgical applications for which textile materials are currently used. A variety of products and their properties that make them suitable for these applications will be discussed.

Textile materials and products that have been engineered to meet particular needs, are suitable for any medical and surgical application where a combination of strength, flexibility, and sometimes moisture and air permeability are required. Materials used include monofilament and multifilament yarns, woven, knitted, and nonwoven fabrics, and composite structures. The number of applications are huge and diverse, ranging from a single thread suture to the complex composite structures for bone replacement, and from the simple cleaning wipe to advanced barrier fabrics used in operating rooms. These materials can be categorised into four separate and specialised areas of application as follows:

- **Nonimplantable materials** – wound dressings, bandages, plasters, etc.
- **Extracorporeal devices** – artificial kidney, liver, and lung
- **Implantable materials** – sutures, vascular grafts, artificial ligaments, artificial joints, etc.
- **Healthcare/hygiene products** – bedding, clothing, surgical gowns, cloths, wipes, etc.

The majority of the healthcare products manufactured worldwide are disposable, while the remainder can be reused. According to a survey in the USA during the decade 1980–1990, the growth of medical textile products occurred at a compound annual rate of 11%. It is estimated that the annual growth was around 10% during 1991–2000. In western Europe the usage of nonwoven medical products between 1970 and 1994 rose from 3000 tonnes to 19700 tonnes[1] (Fig. 15.1). The medical



15.1 Nonwoven medical products in western Europe.

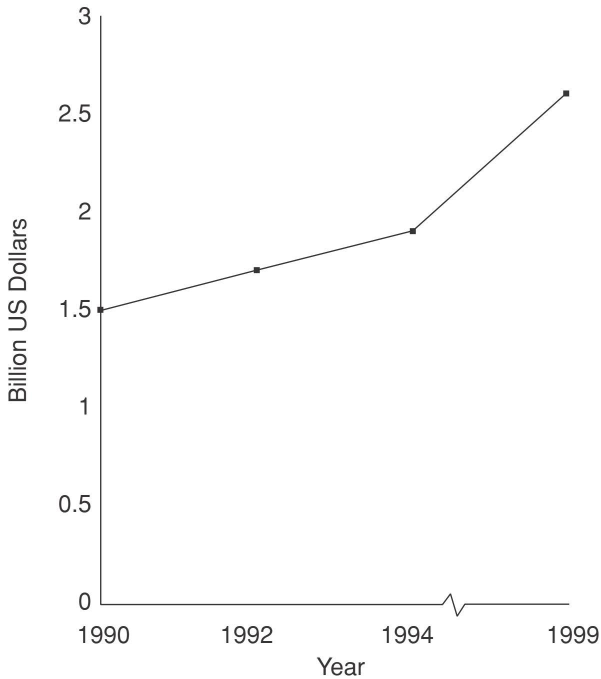
product sales of textile-based items in the USA amounted to \$11.3 billion in 1980 and \$32.1 billion in 1990. This figure is expected to have reached a staggering \$76 billion by the year 2000.[2] The US market for disposable healthcare products alone was estimated to rise from \$1.5 billion in 1990 to \$2.6 billion in 1999[3] (Fig. 15.2). In Europe, medical textiles already have a 10% share of the technical textiles market, with 100000 tonnes of fibre, a growth rate of 3–4% per year and a market of US\$7 billion.[32]

Although textile materials have been widely adopted in medical and surgical applications for many years, new uses are still being found. Research utilising new and existing fibres and fabric-forming techniques has led to the advancement of medical and surgical textiles. At the forefront of these developments are the fibre manufacturers who produce a variety of fibres whose properties govern the product and the ultimate application, whether the requirement is absorbency, tenacity, flexibility, softness, or biodegradability.[4] A number of reviews concerning textile materials for medical applications have also been reported elsewhere.[5–7]

15.2 Fibres used

15.2.1 Commodity fibres

Fibres used in medicine and surgery may be classified depending on whether the materials from which they are made are natural or synthetic, biodegradable or nonbiodegradable. All fibres used in medical applications must be non-toxic, nonallergenic non-carcinogenic, and be able to be sterilised without imparting any change in the physical or chemical characteristics.



15.2 Disposable healthcare products in the USA.

Commonly used natural fibres are cotton and silk but also included are the regenerated cellulosic fibres (viscose rayon); these are widely used in nonimplantable materials and healthcare/hygiene products. A wide variety of products and specific applications utilise the unique characteristics that synthetic fibres exhibit. Commonly used synthetic materials include polyester, polyamide, polytetrafluoroethylene (PTFE), polypropylene, carbon, glass, and so on. The second classification relates to the extent of fibre biodegradability. Biodegradable fibres are those which are absorbed by the body within 2–3 months after implantation and include cotton, viscose rayon, polyamide, polyurethane, collagen, and alginate. Fibres that are slowly absorbed within the body and take more than 6 months to degrade are considered nonbiodegradable and include polyester (e.g. Dacron), polypropylene, PTFE and carbon.[8]

15.2.2 Speciality fibres

A variety of natural polymers such as collagen, alginate, chitin, chitosan, and so on, have been found to be essential materials for modern wound dressings.[9] Collagen, which is obtained from bovine skin, is a protein available either in fibre or hydrogel (gelatin) form. Collagen fibres, used as sutures, are as strong as silk and are biodegradable. The transparent hydrogel that is formed when collagen is crosslinked in 5–10% aqueous solution, has a high oxygen permeability and can be processed into soft contact lenses.[10] Calcium alginate fibres are produced from seaweed of the type Laminariae.[11] The fibres possess healing properties, which have proved to be effective in the treatment of a wide variety of wounds, and dressings comprising calcium alginate are non-toxic, biodegradable and haemostatic.[12] Chitin, a polysaccharide that is obtained from crab and shrimp shells, has excellent antithrombogenic characteristics, and can be absorbed by the body and promote healing. Chitin nonwoven fabrics used as artificial skin adhere to the body stimulating new skin formation which accelerates the healing rate and reduces pain. Treatment of chitin with alkali yields chitosan that can be spun into filaments of similar strength to viscose rayon. Chitosan is now being developed for slow drug-release membranes.[10] Other fibres that have been developed include polycaprolactone (PCL) and polypropiolactone (PPL), which can be mixed with cellulosic fibres to produce highly flexible and inexpensive biodegradable nonwovens.[13] Melt spun fibres made from lactic acid have similar strength and heat properties as nylon and are also biodegradable.[14] Microbiocidal compositions that inhibit the growth of microorganisms can be applied on to natural fibres as coatings or incorporated directly into artificial fibres.[15]

15.3 Non-implantable materials

15.3.1 Introduction

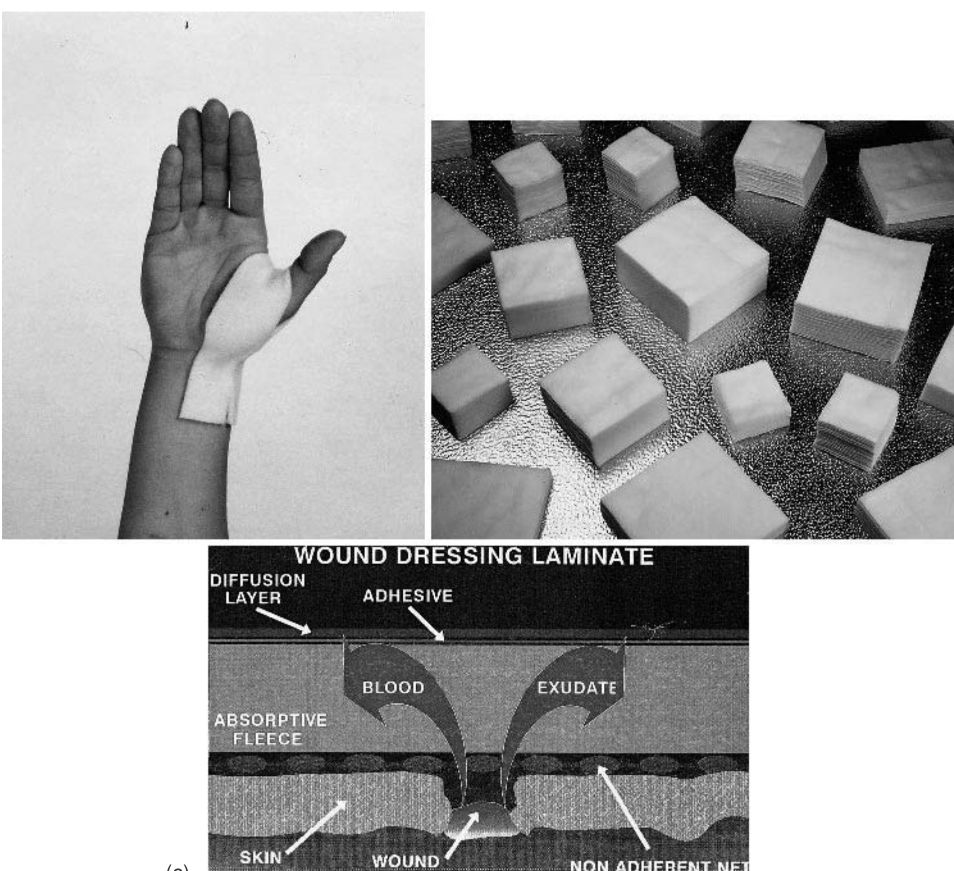
These materials are used for external applications on the body and may or may not make contact with skin. Table 15.1 illustrates the range of textile materials employed within this category, the fibres used, and the principal method of manufacture.

Table 15.1 Non-implantable materials

Product application	Fibre type	Manufacture system
Woundcare		
absorbent pad	Cotton, viscose	Nonwoven
wound contact layer	Silk, polyamide, viscose, polyethylene	Knitted, woven, nonwoven
base material	Viscose, plastic film	Nonwoven, woven
Bandages		
simple inelastic/elastic	Cotton, viscose, polyamide, elastomeric yarns	Woven, knitted, nonwoven
light support	Cotton, viscose, elastomeric yarns	Woven, knitted, nonwoven
compression	Cotton, polyamide, elastomeric yarns	Woven, knitted
orthopaedic	Cotton, viscose, polyester polypropylene, polyurethane foam	Woven, nonwoven
Plasters	Viscose, plastic film, cotton, polyester, glass, polypropylene	Knitted, woven, nonwoven
Gauzes	Cotton, viscose	Woven, nonwoven
Lint	Cotton	Woven
Wadding	Viscose, cotton linters, wood pulp	Nonwoven

15.3.2 Wound care

A number of wound dressing types are available for a variety of medical and surgical applications (Fig. 15.3). The functions of these materials are to provide protection against infection, absorb blood and exudate, promote healing and, in some instances, apply medication to the wound. Common wound dressings are composite materials consisting of an absorbent layer held between a wound contact layer and a flexible base material. The absorbent pad absorbs blood or liquids and provides a cushioning effect to protect the wound. The wound contact layer should prevent adherence of the dressing to the wound and be easily removed without disturbing new tissue growth. The base materials are normally coated with an acrylic adhesive to provide the means by which the dressing is applied to the wound.[16] Developments in coating technology have led to pressure sensitive adhesive coatings that contribute to wound dressing performance by becoming tacky at room temperature but remain dry and solvent free. The use of collagen, alginate, and chitin fibres has proved successful in many medical and surgical applications because they contribute significantly to the healing process. When alginate fibres are used for wound contact layers the interaction between the alginate and the exuding wound



15.3 Wound dressings. (a) and (b) wound dressings, (c) wound dressing concept.

creates a sodium calcium alginate gel. The gel is hydrophilic, permeable to oxygen, impermeable to bacteria, and contributes to the formation of new tissue.[17]

Other textile materials used for wound dressing applications include gauze, lint, and wadding. Gauze is an open weave, absorbent fabric that when coated with paraffin wax is used for the treatment of burns and scalds. In surgical applications gauze serves as an absorbent material when used in pad form (swabs); yarns containing barium sulphate are incorporated so that the swab is X-ray detectable.[18] Lint is a plain weave cotton fabric that is used as a protective dressing for first-aid and mild burn applications.[19] Wadding is a highly absorbent material that is covered with a nonwoven fabric to prevent wound adhesion or fibre loss.[18]

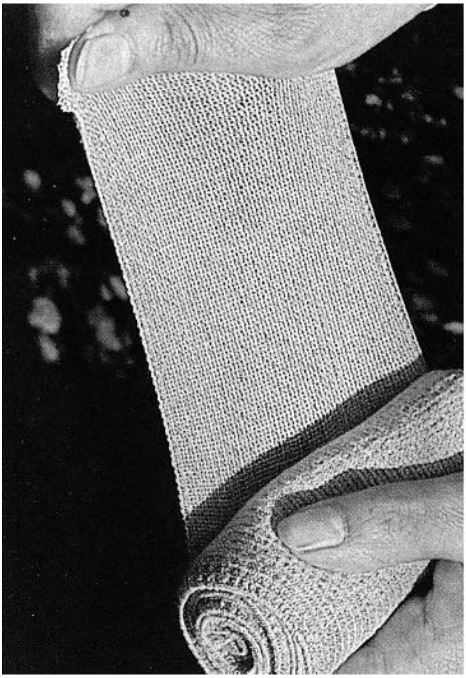
15.3.3 Bandages

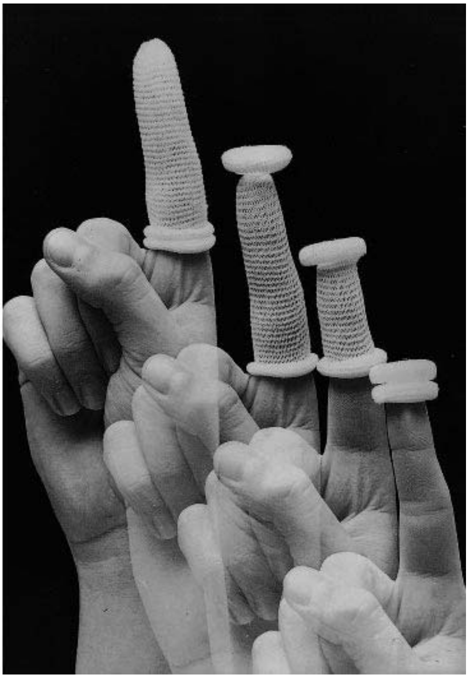
Bandages are designed to perform a whole variety of specific functions depending upon the final medical requirement. They can be woven, knitted, or nonwoven and are either elastic or non-elastic. The most common application for bandages is to hold dressings in place over wounds. Such bandages include lightweight knitted or simple open weave fabrics made from cotton or viscose that are cut into strips then scoured, bleached, and sterilised. Elasticated yarns are incorporated into the fabric structure to impart support and conforming characteristics. Knitted bandages can be produced in tubular form in varying diameters on either warp or weft knitting machines. Woven light support bandages are used in the management of sprains or strains and the elasticated properties are obtained by weaving cotton crepe yarns that have a high twist content. Similar properties can also be achieved by weaving two warps together, one beam under a normal tension and the other under a high tension. When applied under sufficient tension, the stretch and recovery properties of the bandage provides support for the sprained limb.[18,20] Compression bandages are used for the treatment and prevention of deep vein thrombosis, leg ulceration, and varicose veins and are designed to exert a required amount of compression on the leg when applied at a constant tension. Compression bandages are classified by the amount of compression they can exert at the ankle and include extra-high, high, moderate, and light compression and can be either woven and contain cotton and elastomeric yarns or warp and weft knitted in both tubular or fully fashioned forms. Orthopaedic cushion bandages are used under plaster casts and compression bandages to provide padding and prevent discomfort. Nonwoven orthopaedic cushion bandages may be produced from either polyurethane foams, polyester, or polypropylene fibres and contain blends of natural or other synthetic fibres. Nonwoven bandages are lightly needle-punched to maintain bulk and loft. A development in cushion bandage materials includes a fully engineered needlepunched structure which possesses superior cushion properties compared with existing materials.[21]

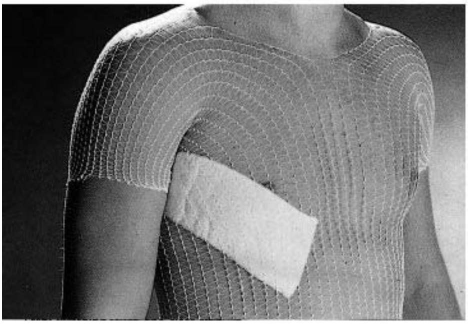
A selection of bandages and non-implantable materials products are shown in Fig. 15.4 and 15.5.

15.4 Extracorporeal devices

Extracorporeal devices are mechanical organs that are used for blood purification and include the artificial kidney (dialyser), the artificial liver, and the mechanical lung. The function and performance of these devices benefit from fibre and textile

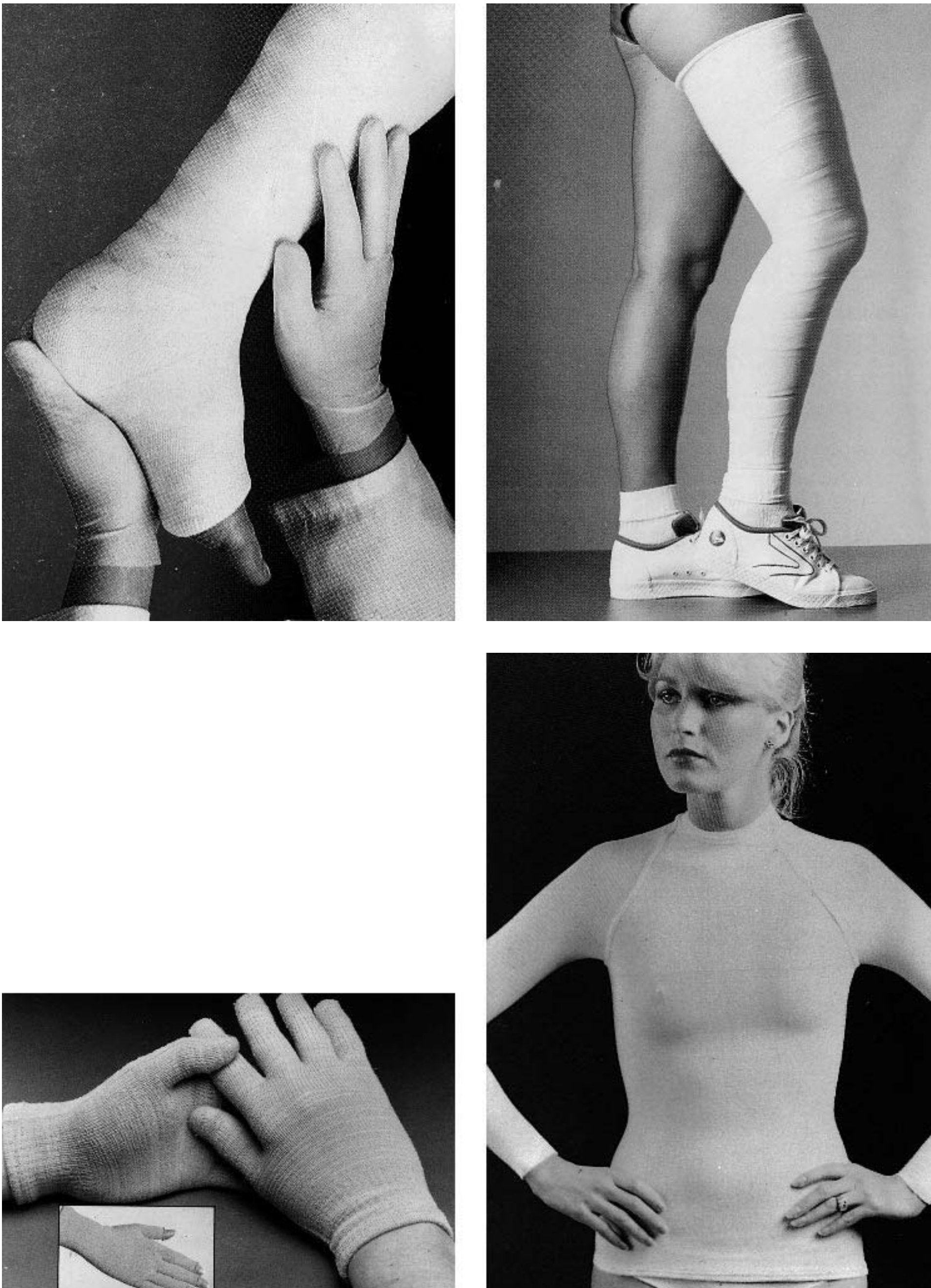

(a)


(b)


(c)

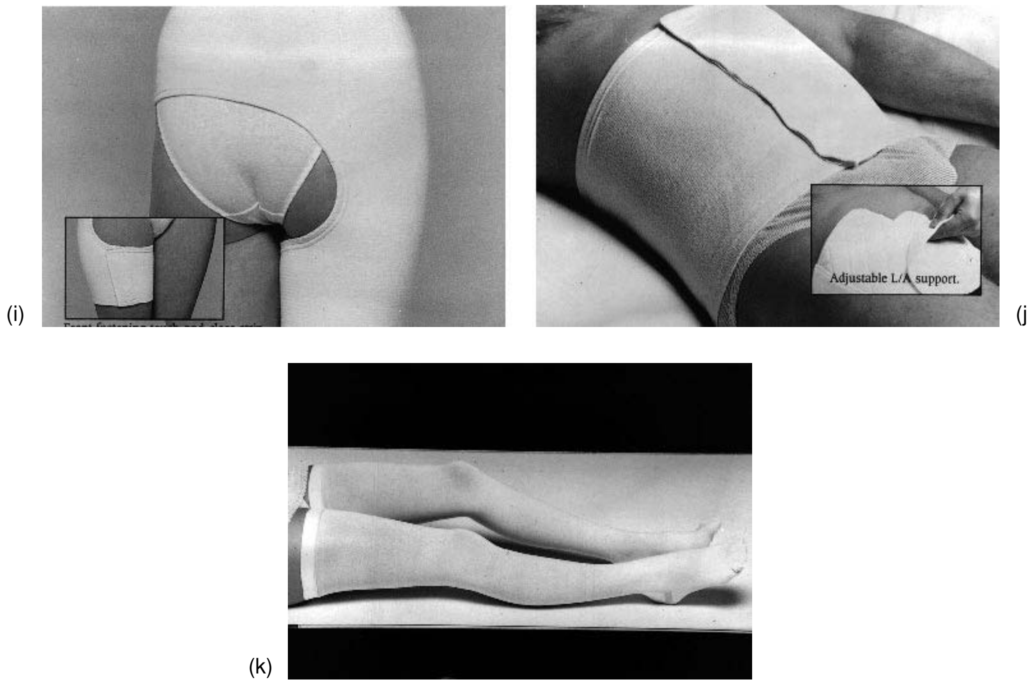
(d)

15.4 Different types of bandages and their application. (a) Elasticated flat bandage, (b) tubular finger bandages, (c) tubular elasticated net garment, (d) tubular support bandages, (e) and (f) orthopaedic casting bandage, (g) pressure gloves, (h) pressure garment, (i) hip spica, (j) lumbar/abdominal support, (k) anti-embolism stockings.



(e) (f) (g) (h)

15.4 *Continued*.



15.4 *Continued.*

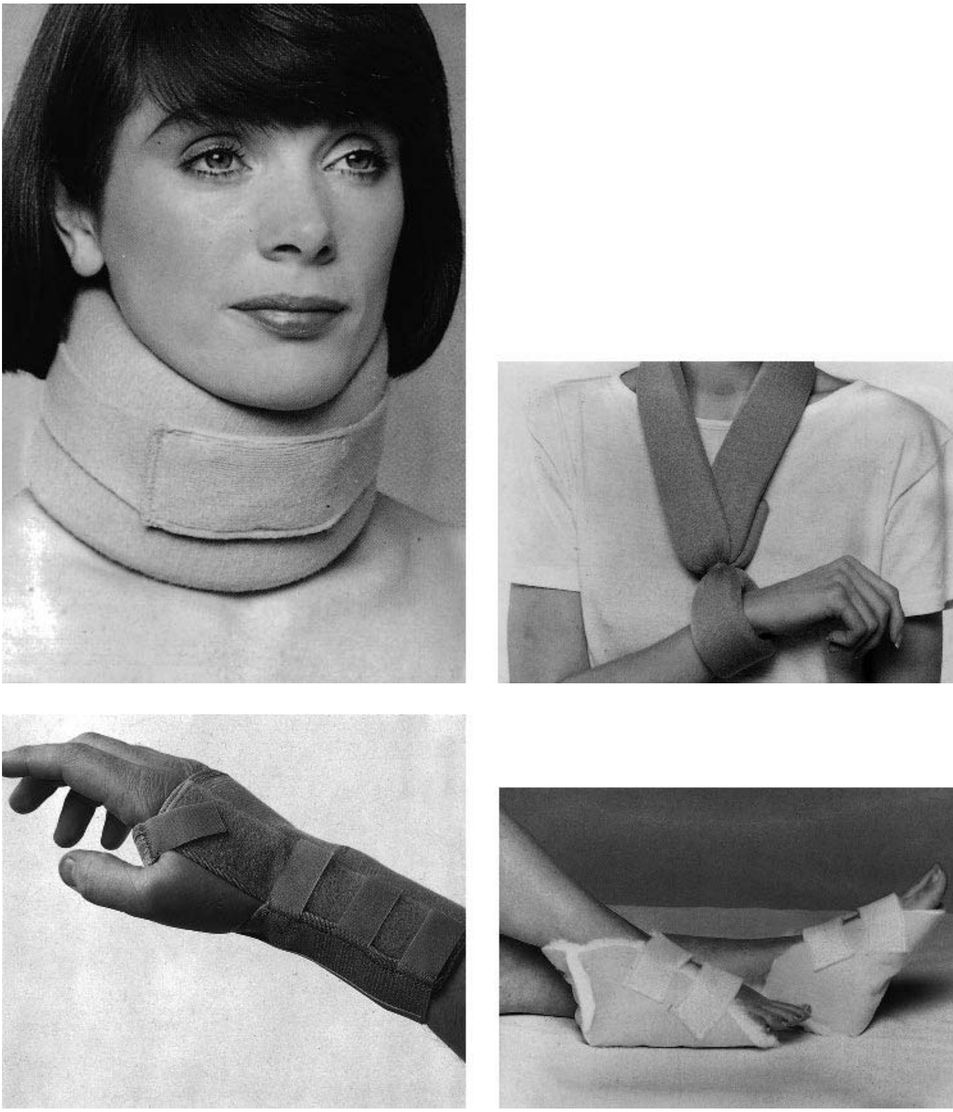
technology. Table 15.2 illustrates the function of each device and the materials used in their manufacture.

The function of the artificial kidney is achieved by circulating the blood through a membrane, which may be either a flat sheet or a bundle of hollow regenerated cellulose fibres in the form of cellophane that retain the unwanted waste materials.[10,22] Multilayer filters composed of numerous layers of needlepunched fabrics with varying densities may also be used and are designed rapidly and efficiently to remove the waste materials.[23] The artificial liver utilises hollow fibres or membranes similar to those used for the artificial kidney to perform their function.[10] The microporous membranes of the mechanical lung possess high permeability to gases but low permeability to liquids and functions in the same manner as the natural lung allowing oxygen to come into contact with the patient's blood.[10,22]

15.5 Implantable materials

15.5.1 Introduction

These materials are used in effecting repair to the body whether it be wound closure (sutures) or replacement surgery (vascular grafts, artificial ligaments, etc.). Table 15.3 illustrates the range of specific products employed within this category with the type of materials and methods of manufacture. Biocompatibility is of prime



(a) (b) (c) (d)

15.5 Miscellaneous surgical hosiery and other products made from non-implantable materials. (a) Cervical collar, (b) foam padded arm sling, (c) adjustable wrist brace, (d) anti-decubitus boots.

importance if the textile material is to be accepted by the body and four key factors will determine how the body reacts to the implant. These are as follows:

1 The most important factor is porosity which determines the rate at which human tissue will grow and encapsulate the implant.
2 Small circular fibres are better encapsulated with human tissue than larger fibres with irregular cross-sections.
3 Toxic substances must not be released by the fibre polymer, and the fibres should be free from surface contaminants such as lubricants and sizing agents.

Table 15.2 Extracorporeal devices

Product application	Fibre type	Function
Artificial kidney	Hollow viscose, hollow polyester	Remove waste products from patients blood
Artificial liver	Hollow viscose	Separate and dispose patients plasma, and supply fresh plasma
Mechanical lung	Hollow polypropylene, hollow silicone, silicone membrane	Remove carbon dioxide from patients blood and supply fresh blood

Table 15.3 Implantable materials

Product application	Fibre type	Manufacture system
Sutures		
biodegradable	Collagen, polylactide, polyglycolide	Monofilament, braided
non-biodegradable	Polyamide, polyester, PTFE, polypropylene, steel	Monofilament, braided
Soft-tissue implants		
artificial tendon	PTFE, polyester, polyamide, silk, polyethylene	Woven, braided
artificial ligament	Polyester, carbon	Braided
artificial cartilage	Low density polyethylene	Nonwoven
artificial skin	Chitin	
eye contact lenses/artificial cornea	Polymethyl methacrylate, silicone, collagen	
Orthopaedic implants		
artificial joints/bones	Silicone, polyacetal, polyethylene	
Cardiovascular implants		
vascular grafts	Polyester, PTFE	Knitted, woven
heart valves	Polyester	Woven, knitted

4 The properties of the polymer will influence the success of the implantation in terms of its biodegradability.

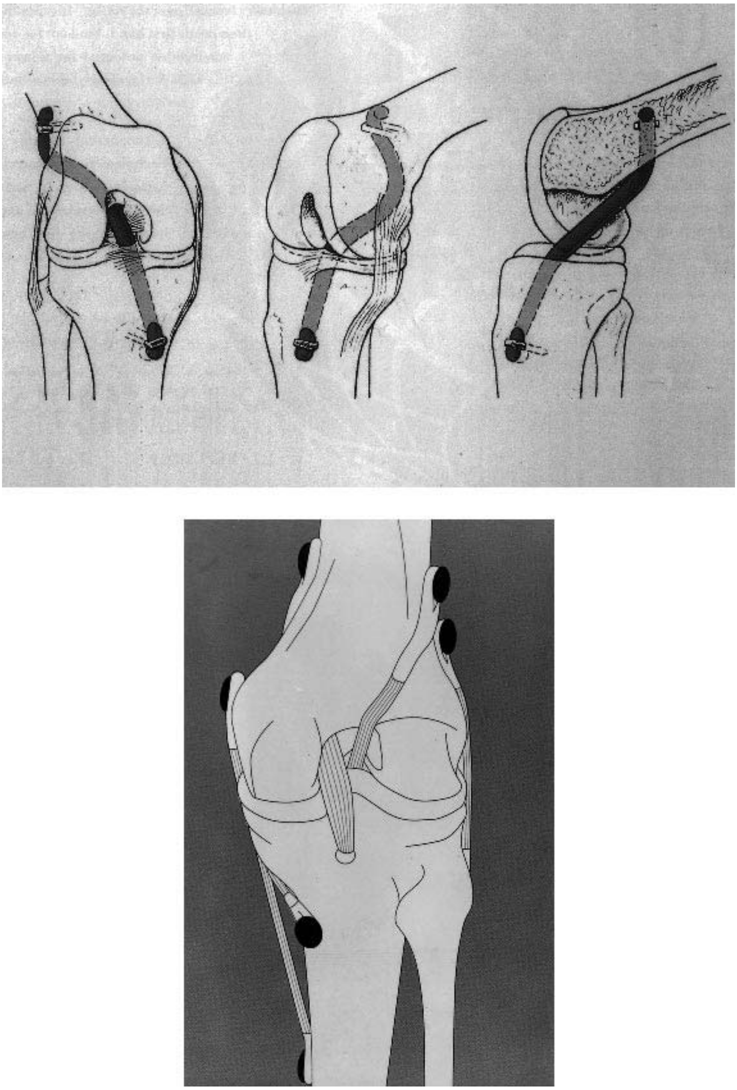
Polyamide is the most reactive material losing its overall strength after only two years as a result of biodegradation. PTFE is the least reactive with polypropylene and polyester in between.[24]

15.5.2 Sutures

Sutures for wound closure are either monofilament or multifilament threads that are categorised as either biodegradable or nonbiodegradable. Biodegradable sutures are used mainly for internal wound closures and nonbiodegradable sutures are used to close exposed wounds and are removed when the wound is sufficiently healed.

15.5.3 Soft-tissue implants

The strength and flexibility characteristics of textile materials make them particularly suitable for soft-tissue implants. A number of surgical applications utilise these characteristics for the replacement of tendons, ligaments, and cartilage in both reconstructive and corrective surgery. Artificial tendons are woven or braided porous meshes or tapes surrounded by a silicone sheath. During implantation the natural tendon can be looped through the artificial tendon and then sutured to itself in order to connect the muscle to the bone. Textile materials used to replace damaged knee ligaments (anterior cruciate ligaments) should not only possess biocompatibility properties but must also have the physical characteristics needed for such a demanding application (Fig. 15.6). Braided polyester artificial ligaments are



15.6 Anterior cruciate ligament prostheses.

strong and exhibit resistance to creep from cyclic loads. Braided composite materials containing carbon and polyester filaments have also been found to be particularly suitable for knee ligament replacement. There are two types of cartilage found within the body, each performing different tasks. Hyaline cartilage is hard and dense and found where rigidity is needed, in contrast, elastic cartilage is more flexible and provides protective cushioning.[25] Low density polyethylene is used to replace facial, nose, ear, and throat cartilage; the material is particularly suitable for this application because it resembles natural cartilage in many ways.[22] Carbon fibre-reinforced composite structures are used to resurface the defective areas of articular cartilage within synovial joints (knee, etc.) as a result of osteoarthritis.[26]

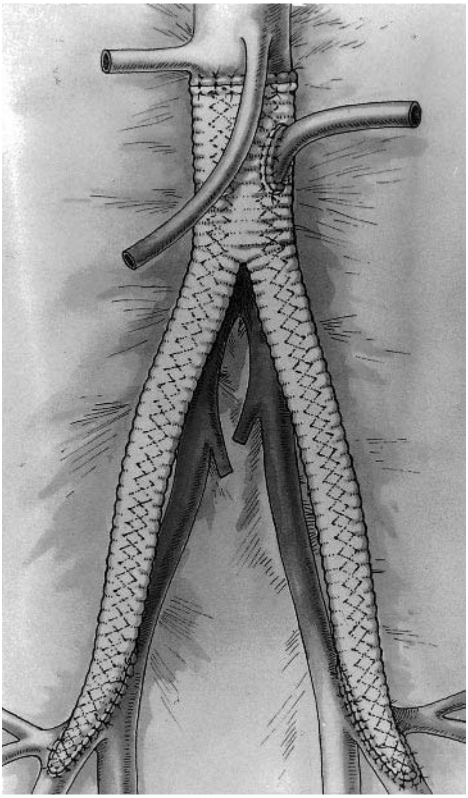
15.5.4 Orthopaedic implants

Orthopaedic implants are those materials that are used for hard tissue applications to replace bones and joints. Also included in this category are fixation plates that are implanted to stabilise fractured bones. Fibre-reinforced composite materials may be designed with the required high structural strength and biocompatibility properties needed for these applications and are now replacing metal implants for artificial joints and bones. To promote tissue ingrowth around the implant a non-woven mat made from graphite and PTFE (e.g. Teflon) is used, which acts as an interface between the implant and the adjacent hard and soft tissue.[27] Composite structures composed of poly(D, L-lactide urethane) and reinforced with polyglycolic acid have excellent physical properties. The composite can be formed into shape during surgery at a temperature of 60 °C and is used for both hard and soft tissue applications.[28] Braided surgical cables composed of steel filaments ranging from 13–130 μm are used to stabilise fractured bones or to secure orthopaedic implants to the skeleton.[29]

15.5.5 Cardiovascular implants

Vascular grafts are used in surgery to replace damaged thick arteries or veins 6 mm, 8 mm, or 1 cm in diameter.[10] Commercially available vascular grafts are produced from polyester (e.g. Dacron) or PTFE (e.g. Teflon) with either woven or knitted structures (Fig. 15.7). Straight or branched grafts are possible by using either weft or warp knitting technology.[18] Polyester vascular grafts can be heat set into a crimped configuration that improves the handling characteristics. During implantation the surgeon can bend and adjust the length of the graft, which, owing to the crimp, allows the graft to retain its circular cross-section.[18,24] Knitted vascular grafts have a porous structure which allows the graft to become encapsulated with new tissue but the porosity can be disadvantageous since blood leakage (haemorrhage) can occur through the interstices directly after implantation. This effect can be reduced by using woven grafts but the lower porosity of these grafts hinders tissue ingrowth; in addition, woven grafts are also generally stiffer than the knitted equivalents.[30]

In an attempt to reduce the risk of haemorrhage, knitted grafts have been developed with internal and external velour surfaces in order to fill the interstices of the graft. Another method is to seal or preclot the graft with the patient's blood during implantation. This is a time-consuming process and its effectiveness is dependent upon the patient's blood chemistry and the skill of the surgeon.[31] Presealed grafts



15.7 Vascular prosthesis.

have zero porosity when implanted but become porous allowing tissue ingrowth to occur. The graft is impregnated with either collagen or gelatin that, after a period of 14 days, degrades to allow tissue encapsulation.[30,31] Artificial blood vessels with an inner diameter of 1.5 mm have been developed using porous PTFE tubes. The tube consists of an inner layer of collagen and heparin to prevent blood clot formation and an outer biocompatible layer of collagen with the tube itself providing strength.[10] Artificial heart valves, which are caged ball valves with metal struts, are covered with polyester (e.g. Dacron) fabrics in order to provide a means of suturing the valve to the surrounding tissue.[27]

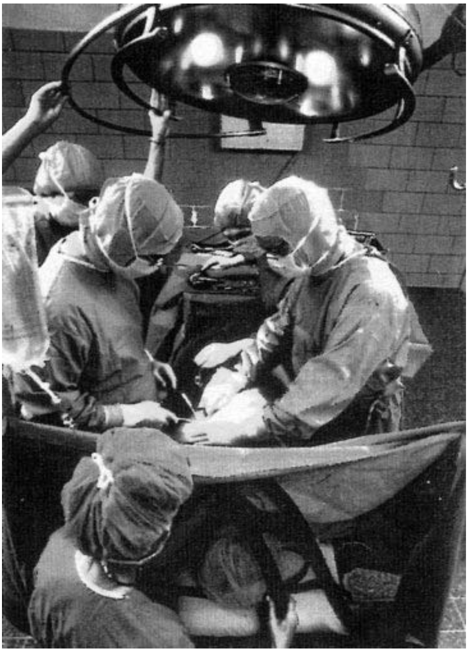
15.6 Healthcare/hygiene products

Healthcare and hygiene products are an important sector in the field of medicine and surgery. The range of products available is vast but typically they are used either in the operating theatre or on the hospital ward for the hygiene, care, and safety of staff and patients. Table 15.4 illustrates the range of products used in this category and includes the fibre materials used and the method of manufacture.

Textile materials used in the operating theatre include surgeon's gowns, caps and masks, patient drapes, and cover cloths of various sizes (Fig. 15.8). It is essential that the environment of the operating theatre is clean and a strict control of infection is

Table 15.4 Healthcare/hygiene products

Product application	Fibre type	Manufacture system
Surgical clothing		
gowns	Cotton, polyester, polypropylene	Nonwoven, woven
caps	Viscose	Nonwoven
masks	Viscose, polyester, glass	Nonwoven
Surgical covers		
drapes	Polyester, polyethylene	Nonwoven, woven
cloths	Polyester, polyethylene	Nonwoven, woven
Bedding		
blankets	Cotton, polyester	Woven, knitted
sheets	Cotton	Woven
pillowcases	Cotton	Woven
Clothing		
uniforms	Cotton, polyester	Woven
protective clothing	Polyester, polypropylene	Nonwoven
Incontinence diaper/sheet		
coverstock	Polyester, polypropylene	Nonwoven
absorbent layer	Wood fluff, superabsorbents	Nonwoven
outer layer	Polyethylene	Nonwoven
Cloths/wipes	Viscose	Nonwoven
Surgical hosiery	Polyamide, polyester, cotton elastomeric yarns	Knitted



15.8 Surgical garments.

maintained. A possible source of infection to the patient is the pollutant particles shed by the nursing staff, which carry bacteria. Surgical gowns should act as a barrier to prevent the release of pollutant particles into the air. Traditionally, surgical gowns are woven cotton goods that not only allow the release of particles from the surgeon but are also a source of contamination generating high levels of dust (lint). Disposable nonwoven surgical gowns have been adopted to prevent these sources of contamination to the patient and are often composite materials comprising nonwoven and polyethylene films for example.[16]

The need for a reusable surgical gown that meets the necessary criteria has resulted in the application of fabric technology adopted for clean room environments, particularly those used for semiconductor manufacture. Surgical masks consist of a very fine middle layer of extra fine glass fibres or synthetic microfibres covered on both sides by either an acrylic bonded parallel-laid or wet-laid nonwoven. The application requirements of such masks demand that they have a high filter capacity, high level of air permeability, are lightweight and non-allergenic. Disposable surgical caps are usually parallel-laid or spun-laid nonwoven materials based on cellulosic fibres. Operating room disposable products and clothing are increasingly being produced from hydroentangled nonwovens. Surgical drapes and cover cloths are used in the operating theatre either to cover the patient (drapes) or to cover working areas around the patient (cover cloths).

Nonwoven materials are used extensively for drapes and cover cloths and are composed of films backed on either one or both sides with nonwoven fabrics. The film is completely impermeable to bacteria while the nonwoven backing is highly absorbent to both body perspiration and secretions from the wound. Hydrophobic finishes may also be applied to the material in order to achieve the required bacteria barrier characteristics. Developments in surgical drapes has led to the use of loop-raised warp-knitted polyester fabrics that are laminated back to back and contain microporous PTFE films in the middle for permeability, comfort and resistance to microbiological contaminants.

The second category of textile materials used for healthcare and hygiene products are those commonly used on hospital wards for the care and hygiene of the patient and includes bedding, clothing, mattress covers, incontinence products, cloths and wipes. Traditional woollen blankets have been replaced with cotton leno woven blankets to reduce the risk of cross-infection and are made from soft-spun twofold yarns which possess the desirable thermal qualities, are durable and can be easily washed and sterilised.[20] Clothing products, which include articles worn by both nursing staff and patients, have no specific requirements other than comfort and durability and are therefore made from conventional fabrics. In isolation wards and intensive care units, disposable protective clothing is worn to minimise crossinfection. These articles are made from composite fabrics that consist of tissue reinforced with a polyester or polypropylene spun-laid web.[16]

Incontinence products for the patient are available in both diaper and flat sheet forms with the latter used as bedding. The disposable diaper is a composite article consisting of an inner covering layer (coverstock), an absorbent layer, and an outer layer. The inner covering layer is either a longitudinally orientated polyester web treated with a hydrophilic finish, or a spun-laid polypropylene nonwoven material. A number of weft- and warp-knitted pile or fleece fabrics composed of polyester are also used as part of a composite material which includes foam as well as PVC sheets for use as incontinence mats. Cloths and wipes are made from tissue paper or nonwoven bonded fabrics, which may be soaked with an antiseptic finish. The cloth or wipe may be used to clean wounds or the skin prior to wound dressing application, or to treat rashes or burns.[26]

Surgical hosiery with graduated compression characteristics is used for a number of purposes, ranging from a light support for the limb, to the treatment of venous disorders. Knee and elbow caps, which are normally shaped during knitting on circular machines and may also contain elastomeric threads, are worn for support and compression during physically active sports, or for protection.

15.7 Conclusions

Textile materials are very important in all aspects of medicine and surgery and the range and extent of applications to which these materials are used is a reflection of their enormous versatility. Products utilised for medical or surgical applications may at first sight seem to be either extremely simple or complex items. In reality, however, in-depth research is required to engineer a textile for even the simplest cleaning wipe in order to meet the stringent performance specifications. New developments continue to exploit the range of fibres and fabric-forming techniques which are available. Advances in fibre science have resulted in a new breed of wound dressing which contribute to the healing process. Advanced composite materials containing combinations of fibres and fabrics have been developed for applications where biocompatibility and strength are required. It is predicted that composite materials will continue to have a greater impact in this sector owing to the large number of characteristics and performance criteria required from these materials. Nonwovens are utilised in every area of medical and surgical textiles. Shorter production cycles, higher flexibility and versatility, and lower production costs are some of the reasons for the popularity of nonwovens in medical textiles.

References

1. P BOTTCHER, *Int. Textile Bull. – Nonwovens/Industrial Textiles*, 1995 **4** 4.
2. G S KWATRA, *Indian Textile J.*, 1992 **102** 18–21.
3. J RUPP, *International Textile Bulletin – Nonwovens/Industrial Textiles*, 1995 **4** 24.
4. K SHAMASH, *Textile Month*, 1989, December 15–16.
5. S C ANAND, *Textile Technol. Int.*, 1994, 220–223.
6. A J RIGBY and S C ANAND, *Technical Textiles Int.*, 1996 **5**(7) 22–28.
7. A J RIGBY and S C ANAND, *Technical Textiles Int.*, 1996 **5**(8) 24–29.
8. M D TELI and N VED V VERMA, *Man-made Textiles India*, 1989 **32** 232–236.
9. Y QIN, C AGBOH, X WANG and D K GILDING, in *Proceedings of Medical Textiles 96 Conference*, Bolton Institute, UK, Woodhead Publishing, Cambridge, 1997, pp. 15–20.
10. T HONGU and G O PHILLIPS, in *New Fibres*, Ellis Horwood, UK, 1990, p. 145.
11. R W MONCRIEFF, in *Man-made Fibres*, 6th edn, Newnes–Butterworths, London, 1975, p. 300.
12. J G COOK, in *Handbook of Textile Fibres – Man-made Fibres*, 5th edn, Merrow, Co. Durham, 1984, p. 153.
13. ANON, *Medical Textiles*, 1993, October 1–2.
14. ANON, *JTN*, 1994, November (No.480) 14.
15. ANON, *Medical Textiles*, 1991, October 1–2.
16. M KRULL, *Nonwoven Bonded Fabrics*, eds J Lunenschloss and W Albrecht, Ellis Horwood, UK, 1985, pp. 399–403.
17. ANON, *Medical Textiles*, 1991, February 1–2.
18. D G B THOMAS, *Textiles*, 1975 **4** 7–12.
19. S Y CHITRE and C SAHA, *Sasmira Technical Digest*, 1987 **20** 12–20.

20. H M TAYLOR, *Textiles*, 1983, **12** 77–82.
21. A J RIGBY, S C ANAND, M MIRAFTAB and G COLLYER, in *Proceedings of Medical Textiles 96 Conference*, Bolton Institute, UK, Woodhead Publishing, Cambridge, 1997, pp. 35–41.
22. P R CHATTERJI, *J. Sc. Ind. Res.*, April **46**, 1987, pp. 14–16.
23. L BERGMANN, *Technical Textiles Int.*, 1992, September 14–16.
24. R W SNYDER, in *High-tech Fibrous Materials*, eds T L Vigo and A F Turbak, ACS Symposium Series 457, 1991, pp. 124–131.
25. C R SCHNEIDERMAN, in *Basic Anatomy and Physiology in Speech and Hearing*, College Hill Press, California, 1984, p. 3.
26. J BROWN, in *Proceedings of Industrial, Technical and Engineering Textiles Conference*, The Textile Institute, Manchester, Paper 8, 1988.
27. A S HOFFMAN, in *Fibre Science*, ed. M Lewin, Applied Polymer Symposium 31, John Wiley & Sons, New York, 1977, p. 324.
28. R F STOREY, J S WIGGINS and A D PUCKETT, *Polymer Reprints*, 1992, **33**(2) 452–453.
29. ANON, *Medical Textiles*, 1994, April 5.
30. ANON, *Medical Textiles*, 1991, February 5–6.
31. ANON, *Medical Textiles*, 1989, September 1–5.
32. S C ANAND, *Techtextil North America*, Atlanta, USA, Conference Proceedings, 24 March, 2000, p. 3.

16

Textiles in defence*

Richard A Scott

Defence Clothing and Textiles Agency, Science and Technology Division, Flagstaff Road, Colchester, Essex CO2 7SS, UK

16.1 Introduction

To be prepared for War is one of the most effectual means of preserving Peace
(George Washington, 1790)[1]

Defence forces on land, sea, or air throughout the world are heavily reliant on technical textiles of all types – whether woven, knitted, nonwoven, coated, laminated, or other composite forms. Technical textiles offer invaluable properties for military land forces in particular, who are required to move, live, survive and fight in hostile environments. They have to carry or wear all the necessities for comfort and survival and thus need the most lightweight, compact, durable, and high performance personal clothing and equipment. The life-critical requirements for protecting individuals from both environmental and battlefield threats have ensured that the major nations of the world expend significant resources in developing and providing the most advanced technical textiles for military use.

16.2 Historical background

Military textile science is not new, and one of the earliest documented studies can probably be credited to Count Rumford, or Benjamin Thompson. Rumford was an American army colonel and scientist who issued a paper in 1792 entitled 'Philosophical Transactions', which reported on the importance of internally trapped air in a range of textile fabrics to the thermal insulation provided by those fabrics.[2] He was awarded the Copley Medal for his paper, as the significance of his discovery was recognised immediately.

16.2.1 Pre-Twentieth century

Up until the end of the 19th century military land battles were fought at close quarters by individual engagements. Military uniforms were designed to be bright, shiny and colourful, both for regimental identification and to intimidate the enemy. 'Danger' colours such as scarlet were widely used, and uniforms carried embellishments such as large epaulettes to increase the apparent width of the shoulders. Tall headwear made from animal furs (bearskin caps), feathers (ostrich), or carrying tall plumes were worn to increase the apparent height of troops. The materials used were all of natural origin, based upon wool and goat hairs, cotton, silk, flax, leather, horsehair, pig bristle, furs from bears, seals, tigers, and leopards, and feathers from birds such as chickens, peacocks and ostriches. Such uniforms were heavy, uncomfortable, and impractical in the field, incurring irreparable damage in a short time.

16.2.2 The twentieth century

At around the turn of the 20th century advances in technology and science provided more lethal long-range weapons with improved sighting. Visual detection equipment became more sophisticated at about this time. These combined effects caused rapid changes in military strategy and tactics, as engagements could be made at a distance. It now became important to hide troops and equipment by blending in with the background. The British Forces adopted khaki coloured uniforms (khaki meaning dung or dust in Persian and Urdu).[3] The first khaki drill (or KD) made from cotton twill or drill entered service for tropical use in 1902, although it had been adopted in the South African Boer War before that time.[4] This cotton drill was found to give insufficient protection from the elements in temperate climates, so that wool worsted serge (twill fabric) uniforms were issued in the khaki or brown colours.

At this time all non-clothing textile items such as tents, shelters, covers, nets, load-carriage items and sleeping systems were made from natural fibres based upon wool, cotton, flax, jute, hemp, sisal, and kapok. Those used for screens, covers and tents were heavy, cumbersome, and prone to degradation by insects, moisture and biological organisms.

The natural environment has always been as big a threat to military forces as enemy action. History provides many instances where the weather defeated armies, navies, and in recent times, air forces. Examples include the Napoleonic wars, World Wars I and II, the Korean War, and more recently, the Falklands War, where countless numbers of forces incurred casualties due to extremes of cold, wet, or hot climates.

In the 1930s the UK War Office became increasingly aware of the need for new and more rational combat dress to meet the needs of mechanisation on land, sea, and in the air. This was to provide better protection, comfort, and practicality.[5]

During World War II advances in textile fibres, fabrics, and treatments saw notable landmarks such as the use of the new fibre 'Nylon' for light strong parachute canopies, and the development of Ventile® cotton fabric for aircrew survival clothing for those who had to ditch into the cold North Sea. Ventile was the first waterproof/water vapour-permeable fabric – invented by scientists at the Shirley Institute (now the British Textile Technology Group). It was based upon low-twist Sea Island cotton yarns in a very tightly woven construction. A very efficient stearamido derivative water-repellent finish (Velan® by ICI) improved the waterproofness of this technical fabric, which is still widely used today by many air forces.

The well-known worsted serge 'battledress' uniform was introduced in 1939. Prototypes of this were made at the Garment Development Section, Royal Dockyard, Woolwich, London. The first formal specification was designated E/1037 of 28th October 1938, issued by the Chief Inspector of Stores and Clothing (CISC).[5]

The 'Denison smock', in a lightweight windproof cotton gaberdine fabric, and bearing rudimentary camouflage patterning, was introduced for airborne paratroopers in 1941. Captain Denison served with a special camouflage unit commanded by Oliver Messel, an eminent theatrical stage designer!

Armoured fighting vehicle crews were issued with a one-piece coverall in black cotton denim. This led to the development of a sand-coloured version in 1944 for desert use.[5]

Woollen serge as a material for field uniforms became obsolete when the United States army introduced the 'layered' combat clothing concept in 1943. The British and other Allies followed this lead, introducing their own layered system as a winter uniform in the Korean War of the 1950s to avoid weather-related casualties.[6]

The next great landmark in combat dress appeared in 1970, when the olive green (OG) 100% cotton satin drill fabric appeared. This was followed in 1972 by the first four-colour disruptively patterned material (DPM) for temperate woodland camouflage. The UK was one of the first forces to introduce such a printed material for combat forces.

From the 1960s to the present day the military textiles, clothing and equipment of all major nations have become ever more sophisticated and diverse. They now utilise the most advanced textile fibres, fabrics and constructions available. It has now been recognised that, no matter how sophisticated weapon systems and equipment become, they ultimately depend for their effectiveness on a human operator to make the final decisions. This has led to significant increases in the reliance on scientific and technical solutions to solve the perennial problems associated with protection of the individual from environmental and battlefield threats, with the need to maintain comfort, survivability and mobility of fighting forces.

16.3 Criteria for modern military textile materials

The main functional criteria for military textiles are dealt with here under a range of headings. These include the physical, environmental, camouflage, specific battlefield threats, flames, heat and flash, and the economic considerations (Tables 16.1 to 16.6).

16.4 Incompatibilities in military materials systems

The functional performance requirements for military textiles are manifold and complex, as indicated in Section 16.3. This complexity inevitably results in serious incompatibilities. It is the attempt to solve these many incompatibilities which occupies the efforts of scientists and technologists.

Table 16.1 Physical requirements for military textiles

Property	Comments
Light weight and Low bulk	Items have to be carried by individuals or vehicles with minimal space available
High durability and Dimensional stability	Must operate reliably in adverse conditions for long periods of time without maintenance.
Cleanable	
Good handle and drape	Comfortable
Low noise emission	Tactically quiet – no rustle or swish
Antistatic	To avoid incendive or explosive sparks

Table 16.2 Environmental requirements

Property	Comments
Water-repellent,	For exterior materials exposed to cold/wet weather
Waterproof,	″ ″
Windproof and	″ ″
Snow-shedding	″ ″
Thermally insulating	For cold climates
Water vapour permeable	For clothing and personal equipment (tents etc.)
Rot-resistant	For tents, covers, nets etc.
UV light resistant	For environments with strong sunlight
Air permeable.	For hot tropical climates
Biodegradable	If discarded or buried

Table 16.3 Camouflage, concealment and deception requirements

Property	Comments
Visual spectrum	Exposed materials match visual colours, texture and appearance of natural backgrounds
Ultraviolet	To match optical properties of snow and ice
Near infrared	To match reflectance of background when viewed by image intensifiers and low light television
Far infrared	To minimise the heat signature emitted by humans and hot equipment. Detection by thermal imagers
Acoustic emissions	Rustle and swish noises emitted by certain textile materials Detected by aural means, unattended ground sensors and microphones
Radar spectrum	Detection of movement by Doppler radar

Table 16.4 Requirements for flame, heat and flash protection

Property	Comments
Flame retardance	Of outer layers exposed to flames and heat
Heat resistance	Avoid heat shrinkage and degradation
Melt resistance	For textiles in contact with the skin
Low smoke emission	To allow escape in confined spaces
Low toxicity	Of combustion products in confined spaces such as ships, submarines, buildings, vehicles

Table 16.5 Specific battlefield hazards

Hazard	Comments
Ballistic fragments	From bombs, grenades, shells, warheads
Low velocity bullets	From hand guns, pistols, etc.
High velocity bullets	From small-arms rifled weapons from 5.56 mm up to 12.7 mm calibre
Flechettes	Small, sharp, needle shaped projectiles
Chemical warfare agents	Including blood agents, nerve agents, vessicants
Biological agents	Bacteria, toxins, viruses
Nuclear radiation	Alpha, beta and gamma radiation
Directed energy weapons (DEW)	Includes laser rangefinders and target designators

Table 16.6 Economic considerations

Property	Comments
Easy-care	Smart, non-iron, easily cleanable
Minimal maintenance	Maintenance facilities not available in the field
Long storage life	War stocks need to be stored for 10–20 years.
Repairable	Repairable by individuals or HQ workshops
Decontaminable or disposable	Against nuclear, biological or chemical contamination
Readily available	From competitive tendering in industry against a standard or specification
Minimal cost	Bought by taxpayers and other public funding

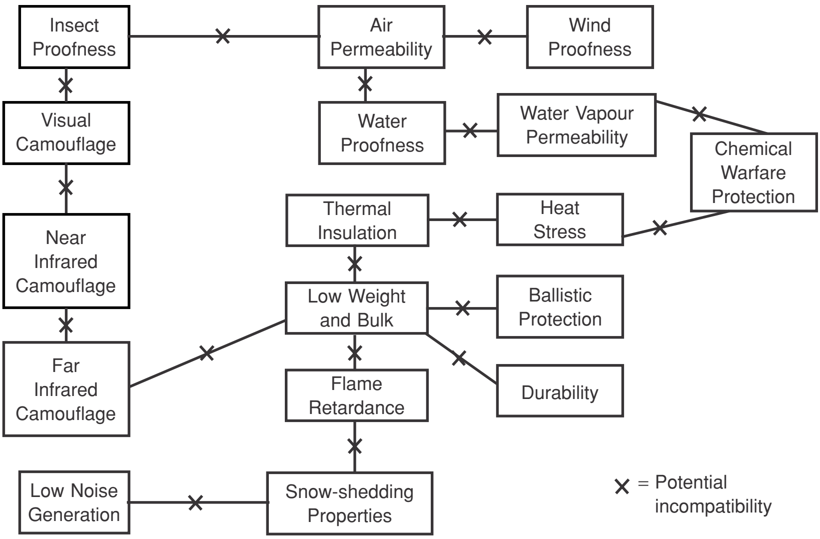
Figure 16.1 shows the relationships between the properties of textile material systems. A cross between two properties highlights a particular problem.[7]

If we start the interpretation of Fig. 16.1 at the box marked 'Low Weight and Bulk', we can see that it is difficult to produce high durability textiles at low weight and good thermal insulation at low bulk. Ballistic protection requires the use of heavy, bulky, relatively inflexible materials. Commodity artificial fibres such as nylon and polyester are widely used, but suffer from their lack of flame retardance. Good snow-shedding properties are provided by flat continuous filament fabrics which are not readily available in flame-retardant forms. Continuous filament fabrics tend to be noisy, producing a characteristic 'swishing' or 'rustling' noise when rubbed or crumpled.

If we provide materials which offer ballistic protection against bullets and bomb fragments, the ballistic packs also offer high thermal insulation, which causes heat stress in the wearer. If we consider the thermophysiological effects further, we encounter the classic problem of providing waterproof fabrics which are permeable to water vapour and air. If water vapour permeability is limited, the problem of activity related heat stress occurs. Conversely, water vapour and air permeable fabrics do not readily provide barriers to chemical warfare agents.

Air-permeable fabrics which are ideal in hot tropical climates, allow biting insects such as mosquitos to penetrate the fabrics. Moreover, many insects are attracted to the printed visual camouflage colours, which include green, khaki and brown.

Camouflage properties are required to cover a wide range of the electromagnetic spectrum, including ultraviolet (<400 nm), visible range (400–800 nm), the near-infrared (NIR) (750–1200 nm), and the far-infrared (FIR) (2600–14 000 nm =



16.1 Incompatibilities in combat materials systems.

2.6–14 μm). Whilst it is relatively easy to to print a wide range of textile fibre types with colour fast dyes of the correct visual shades, it is more difficult to achieve NIR and FIR cover on the same fabric. Artificial fibres such as nylon, polyester, aramids, modacrylics and polyolefins cause particular problems. These requirements are discussed further in Section 16.10.

Since the mid 1970s, research and development effort has resulted in improved knowledge, new products and processes which can go some way towards solving and eliminating these incompatibilities, many of which are discussed later in this chapter.

16.5 Textiles for environmental protection

Military forces have to be prepared to operate in all parts of the globe from arctic, through temperate, to jungle and desert areas. As such they experience the widest range of climatic conditions possible, encountering rain, snow, fog, wind, lightning, sunlight, and dust. They have to survive the attendant heat, cold, wetness, UV light, windchill and other discomforts on land, sea, and in the air. Defence Standard 00-35[8] defines the worldwide climatic conditions in which men, women, equipment and weapons have to operate effectively.

The environment is considered to have the highest priority where protection of the individual is considered. Whether forces are operating at headquarters, during training, on internal security, or peace-keeping duties, or involved in full scale war, the environment is ever present. The battlefield threats – whilst probably much more life threatening – occur at much less frequent intervals.

16.5.1 Underwear materials

Textile materials used for next-to-skin clothing are primarily worn for hygiene reasons. The thermal insulation properties tend to be less important than the tactile properties and the way the material handles moisture (mainly perspiration) in order to remove it from the skin. Tactile properties are associated with fit, flexibility, roughness, and dermatitic skin reactions.[9] A significant proportion of the population has a true allergic reaction to untreated scaly wool fabrics. Military combat underwear fabrics used by many nations, including the UK, need to be made from non-thermoplastic fibres to minimise contact melt/burn injuries (see Section 16.11 on flame and heat protective materials).

The perspiration and handling properties of knitted underwear materials are extremely critical for mobile land forces such as infantry soldiers, marines and special forces. Their activities range from rapid movement on foot carrying heavy loads, to total immobilisation for long periods when lying in ambush or on covert reconnaissance operations in rural areas. Unlike their civilian counterparts outdoors, military forces cannot choose the level of activity, or wait for better conditions before venturing out. This makes it all the more important to stay dry and comfortable. Sweat-wetted clothing is, at least, uncomfortable, but in the worst situations the loss in dry thermal insulation and the wind chill effect on wet skin and clothing can rapidly lead to hypothermia in cold/wet conditions.

Individuals can characterise the sweat content of a fabric in contact with the skin using a subjective scale of wetness, where 1 is 'dry', 2 and 3 are 'damp', and 4 is 'wet'.[10] Modern laboratory methods allow us to measure the capacity of underwear to handle pulses of sweat from the body.[11] This 'buffering capacity' is measured using a sweating guarded hot plate in accordance with ISO 11092 (The Hohenstein Skin Model Apparatus).[12] The test simulates a condition where the garment is lying on the wearer's wet skin. The passage of water through a sample of the material is measured at intervals. It gives an indication of the water that has passed from the plate into the environment, and also that which has been absorbed from the plate into the sample. The buffering index (Kf) has values between 0 (no water transported) and 1 (all water transported). Values above 0.7 are indicative of 'good' performance. Table 16.7 shows the results for a range of underwear materials[15] based upon special high performance polyester fabrics, and blends with cotton, compared with 100% cotton rib – the UK in-service arctic underwear.[13]

The results show that a wide range of fabrics possess very similar buffering indices when exposed to large amounts of sweat. Values above 0.7 indicate that a fabric will have good wicking and drying properties. The best fabrics in these tests were blends of hollow polyester and cotton in a two-sided (bicomponent) double jersey construction. The 100% cotton military fabric, purported to be a poor fabric

Table 16.7 Sweat buffering indices for a range of underwear fabrics

Underwear fabric	Buffering index (Kf)	Ranking
100% Cotton 1 × 1 rib (olive) (**13**)	0.644	5 =
100% Hollow polyester 1 × 1 rib (olive)	0.641	5 =
100% Quadralobal polyester 1 × 1 rib (olive)	0.720	4
70% Hollow polyester/30% cotton, 2-sided rib	0.731	3
67% Hollow polyester/33% cotton double jersey	0.765	1 =
64% Hollow polyester /36% cotton double jersey	0.764	1 =
72% Quadralobal polyester/28% cotton two-sided rib	0.645	5 =
63% Quadralobal polyester/37% cotton double jersey	0.635	8

for performance underwear, actually performed better than a blend of a special quadralobal polyester and cotton, and equally as well as some of the high performance 100% polyester fabrics specifically developed for sports underwear. The main advantage of non-absorbent synthetic fibres is that they dry more rapidly on the body than cotton fabrics and minimise the the cold 'cling' sensation. These laboratory results are augmented by carefully controlled wear trials and physiological trials with human subjects.[14] The differences in performance are shown to be marginal when worn by highly active humans in outdoor situations.

16.6 Thermal insulation materials

Military forces of many nations need to survive and fight in the most extreme conditions known on earth. The cold/wet regions tend to cause the most severe problems, as it is necessary to provide and maintain dry thermal insulation materials.

The cold/dry areas, including the arctic, antarctic, and mountainous regions require the carriage and use of clothing, sleeping bags, and other personal equipment which possess high levels of thermal insulation. Military forces are prone to sacrificing thermal comfort for light weight and low bulk items. The Royal Marines unofficial motto 'travel light, freeze at night' bears out this assertion.[16] Significant effort has been expended by military research establishments to solve this incompatibility.

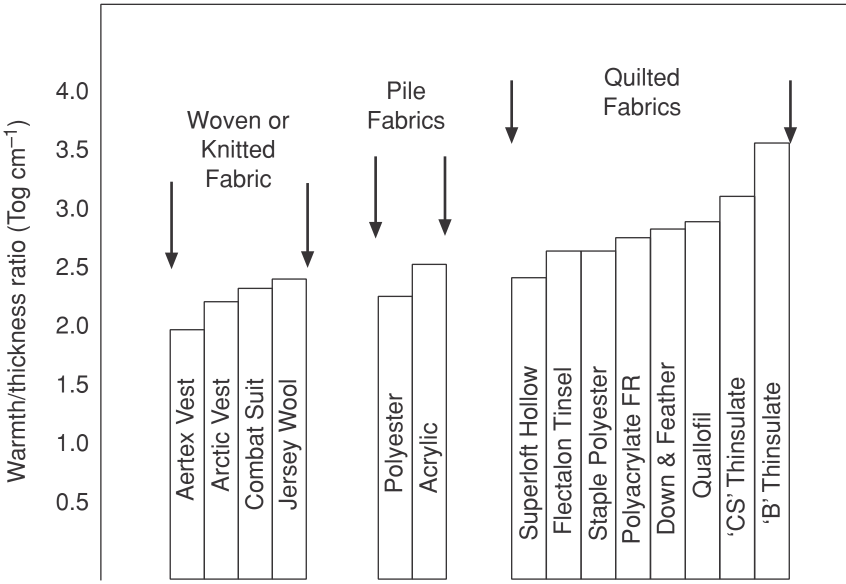
Any fibrous material will offer some resistance to the transmission of heat, because of the air enclosed between and on the surface of the fibres. What really determines the efficiency of the fibrous insulator is the ratio of fibre to air, and the way in which the fibres are arranged in the system. An efficient insulator will be composed of about 10–20% of fibre and 80–90% of air, the fibre merely acting as a large surface area medium to trap still air.[17] There is a secondary effect that is governed by the diameter of the fibres. Large numbers of fine fibres trap more still air, owing to the high specific surface area. However, fine fibres give a dense felt-like batting. There is a compromise between fineness and flexural rigidity which gives the fibre the ability to maintain a degree of 'loft', resilience and recovery from compression which is essential for clothing and sleeping bags. Finer fibre battings are more suitable for insulated footwear and handwear, where low thickness is an important factor.

16.6.1 Insulation efficiency

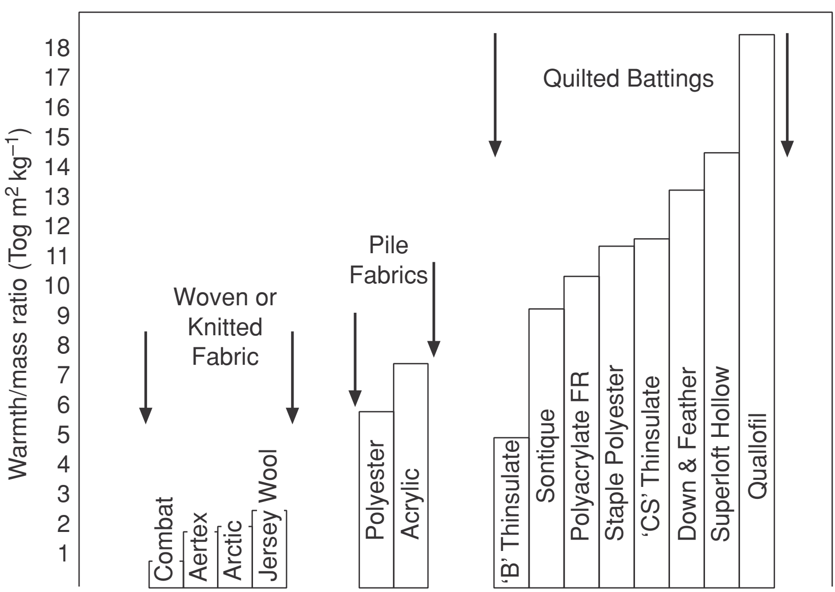
The insulation efficiency of military clothing and equipment is critical, as we endeavour to achieve the highest insulation value at the lowest weight and thickness. Figure 16.2 shows the warmth/thickness ratios in Tog per centimetre for a range of woven, knitted, pile and quilted textile assemblies.[18] The Tog is the SI unit of thermal insulation, measured on a 'Togmeter'.[19] The definition of the Tog unit is: 1 Tog = m^2 K/10 Watts.

Figure 16.2 shows that the warmth/thickness values only vary over a small range, although there is an increase in the value for microfibre products such as Thinsulate®.

If we take the same materials and measure them on a warmth to weight basis (Tog $m^2 kg^{-1}$) we can see from Fig. 16.3 that there is now a significant difference in



16.2 Warmth/thickness efficiency ratio of textile materials.



16.3 Warmth/mass efficiency of textile materials.

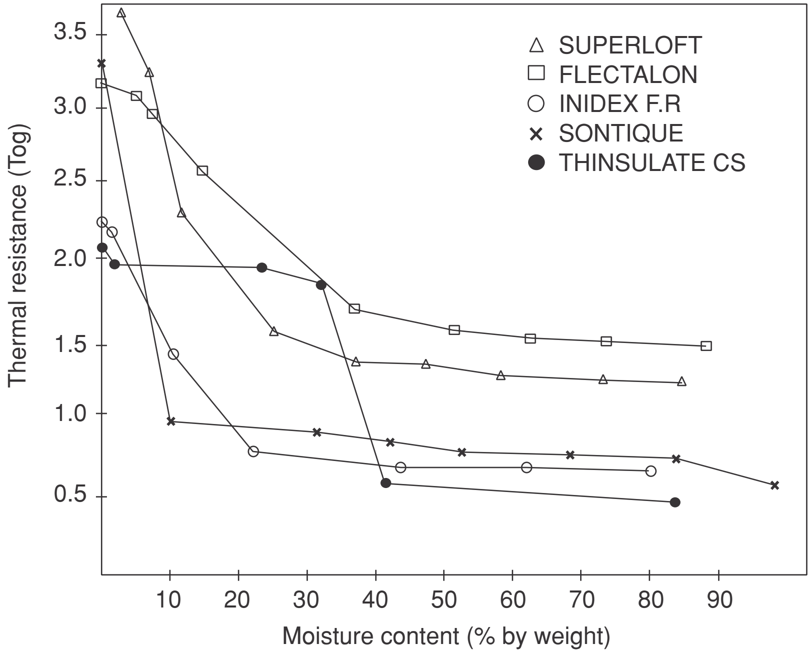
efficiency. Woven and knitted fabrics offer poor insulation for their mass. The pile fabrics are intermediate in efficiency, but the quilted battings are the most efficient. Hollow fibres and down fillings are 13 to 17 times more efficient than a polyester/cotton woven fabric if insulation needs to be carried by the individual.

16.6.2 Effect of moisture on insulation

Any fibrous, porous insulation material is adversely affected by the presence of moisture, whether this is perspiration or rain. Replacing air of low thermal conductivity by water of high conductivity is the primary cause. Moreover, fibrous materials, particularly pile fabrics or quilted battings, have a high affinity for wicking and entrapping large amounts of moisture. Figure 16.4 shows the dramatic effect on a range of quilted battings. The presence of 10–20% by weight of moisture is sufficient to cause up to 50% loss in the dry insulation value.[20] All military personnel are trained to look after their arctic clothing according to the following phrases:

- Keep it **C**lean
- Do not **O**verheat
- Wear it in **L**ayers
- Keep it **D**ry

At regular intervals reflective metallised insulation materials appear on the market which claim to offer improved insulation performance in clothing and sleeping bags, by reflecting back body heat, and being unaffected by moisture. Unfortunately, these claims do not stand close scrutiny, as the reflective component is not used in a way which offers any advantages for active humans operating outdoors on Earth.[17] Such materials operate by reflecting radiant energy, and work well in the vacuum of space, or where large temperature differences occur. On Earth, the major modes of heat loss outdoors are convection and conduction.



16.4 Loss of thermal insulation in wet battings.

16.7 Water vapour permeable/waterproof materials

One of the basic incompatibilities in technical textiles is that associated with providing waterproof materials which allow free passage of water vapour (perspiration). Without this facility, physiological problems can occur when impermeable clothing is worn by highly active soldiers, marines, and special forces.[21] Table 16.8 shows the consequences of such situations.

In the most extreme war operations individuals cannot choose either the climatic conditions or the intensity of their activities. This can result in injury or death due to hypothermia or hyperthermia.

Over the twenty years since around 1980, appreciable effort has been expended by polymer and textile manufacturers to solve this problem. There are now on the market a wide range of woven, coated, or laminated fabrics which are waterproof and water vapour permeable. Many national forces are issued with combat clothing and equipment which provide these properties.

Table 16.8 Effects of wearing impermeable clothing in different conditions

Conditions	Activity	Consequences
1. Cold/wet climate	Medium activity	Discomfort
2. Cold/wet climate in sweat-wetted clothing	High activity followed by low activity	Hypothermia (cold stress)
3. Hot/moist climate and wearing protective clothing	High activity	Hyperthermia (heat stress)

16.7.1 Types of water vapour permeable barrier fabrics

There are three main categories of materials of this type:[22]

1 **High density woven fabrics –** are typified by Ventile cotton fabric. There are also a range of fabrics based on woven microfibre polyester of Japanese origin such as Teijin Ellettes®, Unitika Gymstar®, and Kanebo Savina®. Ventile was originally developed for military use during World War II, and is still widely used by military and civilian forces.[23]

2 **Microporous coatings and films** – are widely available in many variants. Such membranes are typified by having microporous voids of pore sizes from 0.1–5 μm. The most well-known product, Gore-Tex®, utilises a microporous polytetrafluoroethylene (PTFE) membrane. There are also a range of products based upon polyurethane chemistry, with tradenames such as Cyclone®, Entrant®, and Aquatex®. Other products are based upon microporous acrylic, (Gelman Tufferyn®), and polyolefin (Celguard®). In some cases these membranes or coatings incorporate a top coat of a hydrophilic polymer to resist contamination of the pores by sweat residues, and penetration by low surface tension liquids.[22]

3 **Hydrophilic solid coatings and films** – in contrast to microporous films, the hydrophilic products are continuous pore/free solid films. As such they have a high resistance to ingress of liquids. Diffusion of water vapour is achieved by the incorporation of hydrophilic functional groups into the polymer such as -O-, CO-, -OH, or -NH_2 in a block copolymer. These can form reversible hydrogen bonds with the water molecules, which diffuse through the film by a stepwise action along the molecular chains.[24]

Many products are based upon segmented polyurethanes with polyethylene oxide adducts, and have trade names such as Witcoflex Staycool®. This particular polymer was originally developed for military use with research funding from the Defence Clothing and Textiles agency (formerly the Stores and Clothing Research and Development establishment, Colchester, Essex)

Other European market products are based upon a modified type of polyester into which polyether groups have been introduced.[25] The film laminate Sympatex® is typical of this class of textile.

16.7.2 Relative performance of vapour permeable barrier textiles

Work carried out by the UK Defence Clothing and Textiles Agency on a wide range of products[22] has enabled general comparisons of performance to be made. Table 16. 9 compares the main properties in terms of star ratings.

Physiological trials using instrumented human subjects wearing identical garments made from a range of materials have been made.[26] The results show that the differences in vapour permeability between materials are much smaller when worn in garment form than the laboratory test figures would indicate.

Table 16.9 Comparison of performance of water vapour permeable fabrics

Type of barrier	Water vapour permeability	Liquid proofness	Cost	Comments
PTFE laminates	*****	*****	High	Market leader, versatile, expensive
Microporous polyurethanes	** to *****	*** to *****	Medium to high	Widely used, reasonable durability
Hydrophilic polyurethanes and polyesters	** to ***	*** to *****	Low to medium	Cheap, widely available, some durability problems
High density woven fabrics	*****	*	Medium to high	Ventile is expensive, waterproofness low
Impermeable coatings	–	** to *****	Low to medium	Uncomfortable

* = Poor, ** = low, *** = medium, ***** = good, ***** = excellent.

16.7.3 Military usage of waterproof/vapour permeable textiles

Table 16.10 shows the range of military items specified by the UK MOD.

16.8 Military combat clothing systems

Current combat clothing systems are based upon the layer principle, where each layer performs a specific function in the Combat Soldier 95 (the combat clothing system worn by UK Forces which entered service in 1995) assembly. Details of the

Table 16.10 Military items using vapour permeable barrier fabrics

Water vapour permeable barrier	End item usage	Material specification
PTFE Laminates	Waterproof suits, army, Royal Marines and Royal Air Force, camouflaged;	UK/SC/5444 PS/13/95
	MOD police anorak, black;	UK/SC/4978
	Arctic mittens;	UK/SC/4778
	Insock, boot liners;	PS/04/96
	Cover, sleeping bag, olive;	UK/SC/4978
	Tent, one man	UK/SC/4960
Microporous	Suit, waterproof, aerial erectors	UK/SC/5070
Polyurethane and hydrophilic polyurethane	Suit, foul weather, Royal Navy	PS/15/95
	Gaiter, snow, general service	UK/SC/5535
Ventile	Coverall, immersion, aircrew, RAF;	
high density	Jacket, windproof, aircraft carrier deck;	
woven cotton	Coveralls, swimmer canoeist	

Table 16.11 Combat Soldier 95 clothing layers

Layer	Material	Specification
Underwear	100% Cotton knitted 1 × 1 rib, olive	UK/SC/4919
Norwegian shirt	100% Cotton, knitted plush terry loop pile, olive	UK/SC/5282
Lightweight combat suit	Cloth, twill, cotton/ polyester, camouflaged DPM, near IRR camouflaged	UK/SC/5300
Windproof field jacket	Cloth, gaberdine, 100% cotton with nylon rip-stop, water-repellent, near IRR, DPM	UK/SC/5394
Fleece pile jacket	Cloth, knitted, polyester, fleece pile, double-faced	UK/SC/5412
Waterproof rain suit	Cloth, laminated, nylon/PTFE/nylon, waterproof/water vapour permeable, DPM, near IRR camouflaged	PS/13/95

composition of the textiles in each layer are given in Table 16.11. This is the basic fighting system to which can be added other special protective layers, including a ballistic protection system comprising body armour and helmet, a nuclear, biological and chemical (NBC) oversuit, and a snow camouflage oversuit.

16.8.1 Thermal and water vapour resistance data for combat clothing systems

The Combat Soldier 95 layered system has been evaluated using a sweating guarded hotplate apparatus (Hohenstein Skin Model) conforming with ISO 11092:1993.[12] Both the thermal resistance (Rct) and the water vapour resistance (Ret) have been measured and are reported here in Table 16.12. The water vapour permeability index (imt) is defined as $S \times$ Rct/Ret, where $S = 60\,\mathrm{Pa\,W^{-1}}$. The imt has values between 0 and 1.

The thermal resistance (Rct) and vapour resistance (Ret) values for each layer are additive, which gives an indication of the total value for the clothing assembly, excluding air gaps, which can add significantly to both values.[27]

Table 16.12 Rct and Ret values for Combat Soldier 95 clothing system

Textile layer	Rct ($m^2 K W^{-1}$)	Ret ($m^2 Pa W^{-1}$)	imt
Cotton underwear	0.03	5.1	0.3
Norwegian shirt	0.05	8.6	0.3
Polyester fleece	0.13	13.4	0.6
Lightweight combat suit	0.01	4.3	0.2
Windproof field jacket	0.005	4.8	0.1
'Breathable' rain suit	0.003	11.2	0.01
Total =	0.228	47.4	–

To gain an insight into the effect of vapour resistance (Ret) on a comfort rating system, we can compare these figures with the requirements laid down in the European Standard EN 343:1996 (Clothing for protection against foul weather). This puts the vapour resistance of clothing layers into three categories or classes, which are used in the CE marking of personal protective equipment, as follows:

- **Class 1 materials** have Ret values greater than 150 $m^2 Pa W^{-1}$, and are considered to be impermeable, i.e. they offer no perceivable comfort to the wearer.
- **Class 2 materials** have Ret values between 20 and 150 $m^2 Pa W^{-1}$, and are rated as medium performance, offering some breathable performance. The majority of products on the market fit into this category.
- **Class 3 materials** have Ret values less than 20 $m^2 Pa W^{-1}$ and have the best performance in terms of 'breathability'.

From Table 16.12 we can see in general that all the materials have class 3 performance, although the total clothing assembly would be a class 2 overall.

16.8.2 Vapour permeability of footwear

Leather military footwear for cold/wet climates can be fitted with a waterproof/vapour permeable liner or 'sock'. Its main purpose is to improve the waterproofness of leather boots. Tests have been carried out[27] using a sweating/guarded hot-plate to measure the Ret value of the leather, the liner, and the complete assembly:

- Sock liner: 23.9 $m^2 Pa W^{-1}$
- Boot leather: 80.2 $m^2 Pa W^{-1}$
- Combined boot + liner: 113.4 $m^2 Pa W^{-1}$

Thus, the leather is seen to be the determining factor here, its high resistance is then increased markedly when worn with a liner. The Ret value for the combination is approaching the level at which sweat condensation inside the boot becomes a problem.

16.8.3 Vapour permeability of sleeping bags

The heat and moisture transport properties of fibrous battings for temperate weight sleeping bags have been measured[27] and appear in Table 16.13. Five variants based on polyester fibres are shown.

Table 16.13 Performance of polyester fibre fillings for sleeping bags

Sleeping bag filling type	Density ($g\,m^{-2}$)	Water vapour resistance ($m^2\,Pa\,W^{-1}$)	Thermal resistance ($m^2\,K\,W^{-1}$)
Polyester fibre	175	48.1	0.45
Polyester fibre	200	53.4	0.51
Polyester 4 hole fibre	200	54.5	0.52
Poly synthetic down	285	45.7	0.31
Mixed denier poly	300	49.6	0.39

The four-hole hollow fibre product has been specified for UK military sleeping bags, and is the most thermally efficient for its weight. Note the approximate relationship between Rct and Ret – as one increases so does the other. The Ret values for such battings are high, even though they are open fibrous structures.

16.9 Camouflage concealment and deception

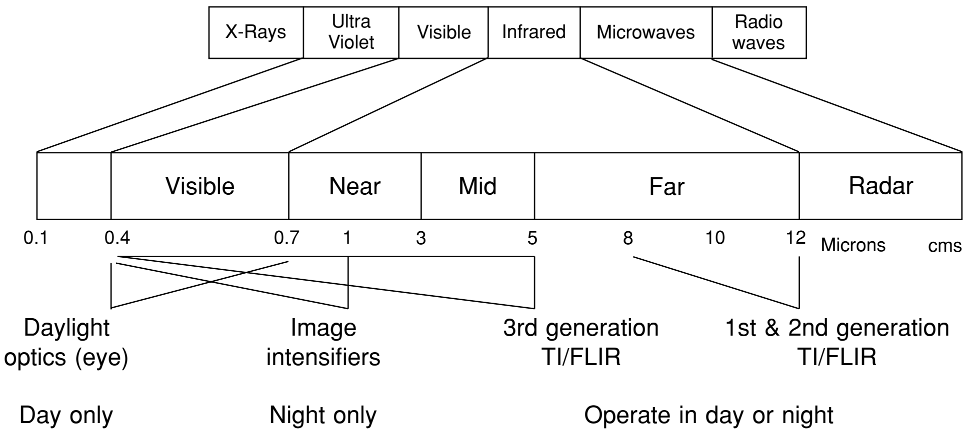
The word camouflage comes from the French word 'camoufler' (to disguise) and was first introduced by the French during World War I to define the concealment of objects and people by the imitation of their physical surroundings, in order to survive. There are earlier examples of the use of camouflage by skirmishing infantry from the 1750s to 1800s, followed by the use of khaki colouring after 1850 in India. In essence, effective camouflage must break up the object's contours, and minimise contrasts between the object and the environment.

Observation in the visual region, either by the eye, or by photography, remains the primary means of military surveillance and target acquisition.[28] However, modern battlefield surveillance devices may operate in one or more wavebands of the electromagnetic spectrum, including the ultraviolet (UV), Near Infra Red (NIR), Far Infra Red (FIR), and millimetric or centimetric radar wavebands. Figure 16.5 shows the relevant parts of the spectrum. A basic objective is that observation and detection should occur at as long a range as possible, and it should be a passive process, that is, it should not be itself detectable. Shining a torch to illuminate an enemy object is likely to meet with unwanted retaliatory action.[29] A notable feature of warfare is that advances in technology proceed in discrete stages. As soon as one threat is countered by technology, another more complex threat emerges. Camouflage research is a good example of this, as new threats in different parts of the spectrum are developed and then subsequently defeated.

Textiles are widely used as the camouflage medium, in the form of light flexible nets, covers, garnishing and clothing items.

16.9.1 Ultraviolet waveband

Only in the snow covered environment is UV observation of military importance. The threat is mainly from photographic systems which use quartz optics and blue/UV sensitive film emulsions. Developments have seen the use of CCD video camera systems which can now operate in this short wavelength region. Snow has a uniform high reflectance at all visible wavelengths, that is, it appears white, but it also continues to have a high reflectance in the UV region. The spectral curves for



16.5 Electromagnetic spectrum.
TI/FLIR = Thermal imaging/forward looking infrared.

light, heavy, and melting snows vary somewhat, as the texture and crystal structures are different.

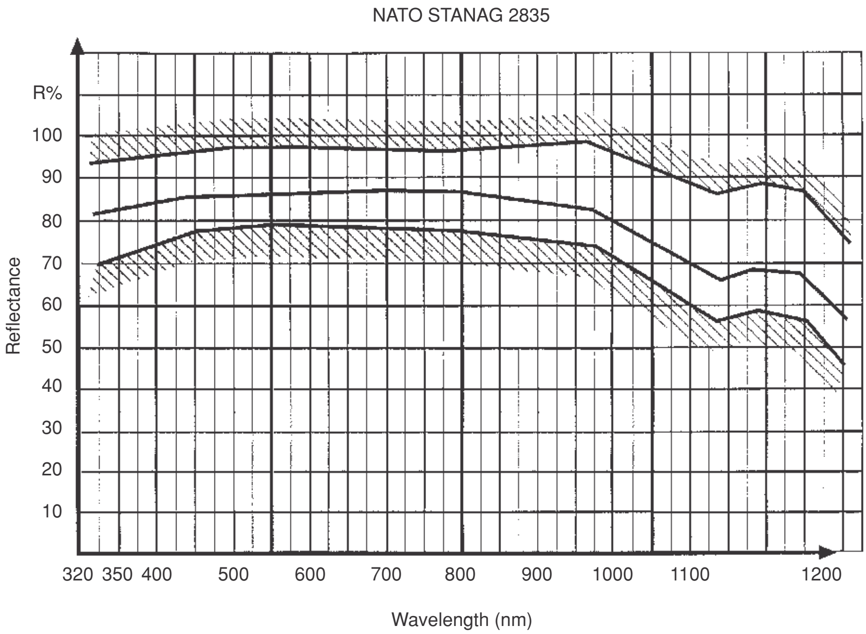
The detection problem occurs with white textiles or coatings, as the titanium dioxide pigment which is commonly used as a low-cost widely available treatment for artificial fibres is visually white, but has low reflectance in the UV. Luckily, other pigments such as barium sulphate are suitable and can be incorporated into textile coatings. Figure 16.6 shows the NATO standard reference curve for the snow camouflage UVR colour.[30] Materials must match this curve to achieve good camouflage. It is interesting to note that the reflectance of snow is between 80 and 98% in the UV and visible bands.

Lightweight nylon or polyester filament fabrics coated with a pigmented acrylic coating are widely used for covers, nets and clothing. The coated fabric is cut or incised into textured shapes or blocks to mimic the snow-laden background. Figure 16.7 shows a typical vehicle concealment net in use.

16.9.2 Visible waveband

In this range we are trying to mimic natural or even artificial backgrounds, not just in terms of colour, but also patterns, gloss and texture. Colour can be measured in terms of tri-stimulus coordinates using a spectrophotometer in the laboratory. Camouflage is one of the unique areas where textile coloration is used for a functional purpose, rather than for aesthetic purposes.

If we consider the vegetated temperate environment as an example, can we define an average or standard background against which to develop woodland camouflage? A tree or bush, for instance, will have a different appearance during different parts of the day as the quality of illumination changes. The leaves and bark also change appearance throughout the seasons of the year, deciduous vegetation



16.6 NATO standard reference curves for snow camouflage.

16.7 Snow camouflage net in use.

showing the widest variation of colour, texture, and appearance from summer to winter. Any measurements or standards which we develop are only modestly accurate, and we have to select colours and patterns which, on average, perform the best. This is still done very empirically, with much trialling of prototypes in the field using direct observation or photographic assessment.

In practice, each military nation has adopted its own visual colours and patterns. Colours often include khaki, green, brown and black, with additional colours such as olive, yellow, orange, pink, grey, beige, and sand to extend use to other urban, rural and desert backgrounds. The UK Disruptively Patterned Material (DPM) printed for clothing uses the first four colours in carefully calculated areas to mimic temperate woodland areas. There is also a two coloured brown and beige pattern for desert use.

Most textile fibres can be dyed to match the visual shades of a standard pattern. Nets, garnishing and covers for vehicle windscreens, machinery and large weapons are often made from lightweight polyurethane or acrylic-coated nylon which is pigmented to give the appropriate visual colours. Figure 16.8 shows soldiers wearing

16.8 Soldiers wearing camouflage-patterned clothing.

clothing in the UK DPM print.[31] This is most effective when viewed with bushes or trees in the immediate vicinity, which is where soldiers tend to conceal themselves. It is not so effective in open grassland, although troops will enhance the effectiveness by covering themselves in freshly cut branches and other vegetation.

16.9.3 Visual decoys

Textile materials are widely used to fabricate and simulate the outline of high value military targets such as aircraft, tanks, missile launchers, and other vehicles. These decoys vary in their complexity depending on the source of the potential attack. If surveillance and target acquisition is at short range, and with sufficient time to study detail, then the decoy has to be a realistic three-dimensional copy of the genuine item. Inflatable decoys made from neoprene or hypalon-coated nylon fabrics have been used to mimic armoured fighting vehicles (AFV), missile launcher/tracker modules, artillery, and other vulnerable equipment. These are cheap and easy to transport and deploy. If target surveillance is at long range and with short acquisition times, as in the case of high speed aerial attack, then the decoys can be a simple two-dimensional representation of the target. As long as it approximates to the shape and size of the original, and casts a shadow that authenticates it, decoys made from fabricated textile materials on a simple supporting frame are adequate for the purpose. Figure 16.9 shows a textile structure developed to mimic the tornado multirole front line aircraft.

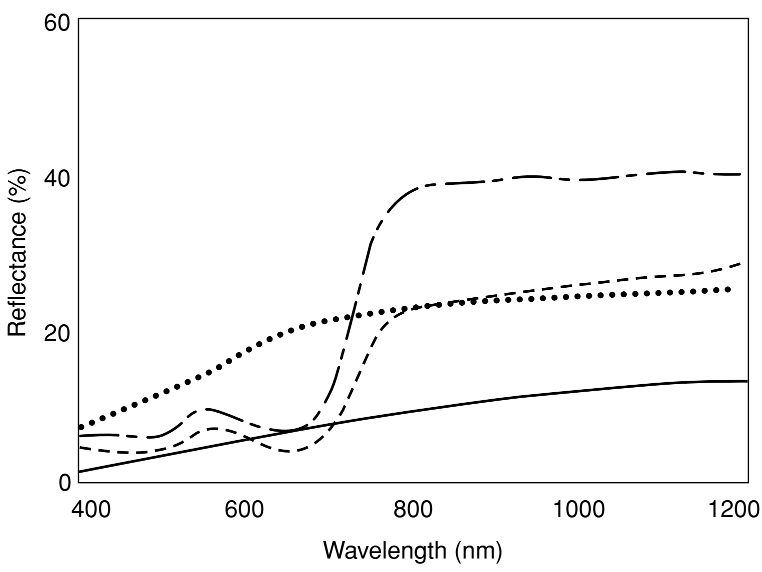
The tactical advantages of decoys are obvious: they confuse the enemy into believing that opposing forces are larger than in reality. They may also cause the enemy to release expensive weaponry and ordnance at worthless targets, wasting valuable mission effort and exposing themselves to the risk of retaliation from 'real' weapons.

16.9 Textile decoy of a tornado aircraft.

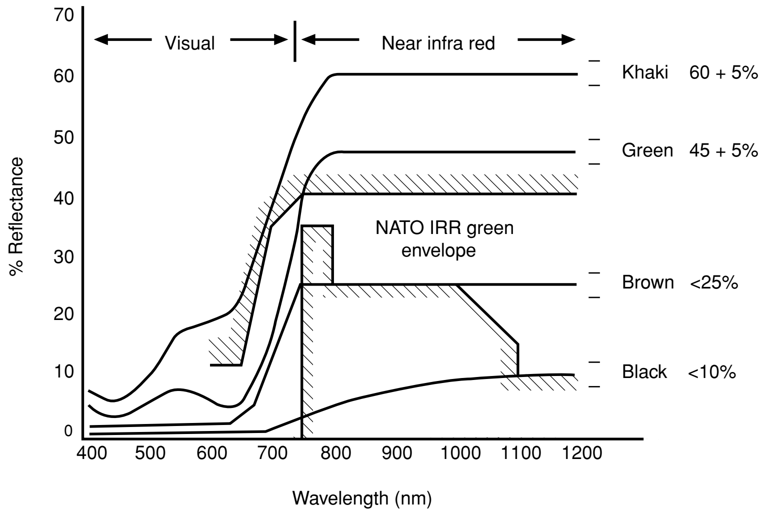
16.9.4 Near infrared camouflage

The NIR region of the spectrum covers the wavelength range from 0.7–2.0 μm, although current camouflage requirements concentrate on the 0.7–1.2 μm range. In this region objects are still 'seen' by reflection. The military camouflage threat is posed by imaging devices which amplify low levels of light, including moonlight and starlight, which go under the generic name of image intensifiers. These can be in the form of monoculars, binoculars, or low-light television systems. The earliest image intensifiers were developed during Word War II[32,33] after many nations had solved the problem of avoiding visual detection by the eye. Modern image intensifiers use microchannel plates (MCP) technology, and gallium arsenide photocathodes. They are now smaller, lighter and more capable than earlier systems, and hence more readily usable. They tend to operate in the range from 0.7–1.0 μm. Modern infrared photographic 'false colour' films tend to work in the range 0.7–1.3 μm[34] but are only useful for photographing installations which are unlikely to move during the time taken to process the film.

The attribute which is required by camouflage to degrade the threat is related to the reflectance spectrum of leaves, bark, branches, and grasses in the NIR. Figure 16.10 shows the reflectance spectrum of natural objects, including leaves.[35] Note the maximum reflectance at 0.55 μm in the visual range which gives rise to the green colour. As we pass into the NIR there is a dramatic rise in reflectance between 0.7 and 0.8 μm, up to about 40% reflectance. This 'chlorophyll rise' or 'edge' has to be matched by the dyes and pigments used in the camouflage textiles. This is a complex problem, as few dyes, coatings, and pigments exhibit this behaviour in the NIR. Moreover, the reflectance of vegetation varies widely: deciduous tree leaves have relatively high infrared reflectance compared with coniferous needles. There is also the change in reflectance with the seasons, as detailed in Section 16.10.2. The overall NIR reflectance in winter tends to be much lower than in summer.



16.10 Typical reflectance curves of natural objects. —-—, Lime tree leaf; … , dry sand; ---, silver fir needle; —, soil. (Reproduced from Ciba-Geigy[35] with permission.)



16.11 Reflectance curves for four-colour disruptively patterned textiles.

Figure 16.11 shows the spectral reflectance curves for a four-colour disruptively patterned printed textile using khaki, (60 ± 5%), green (45 ± 5%), brown (<25%) and black (<10%) colourants. Note that each colour has to meet a specified reflectance value. Moreover, the overall reflectance values, integrated with the area of each colour in the print, have to fall within the envelope for NATO IRR Green[36] in accordance with the equation: $(0.16 \times \text{black}) + (0.35 \times \text{brown}) + (0.34 \times \text{green}) + (0.15 \times \text{khaki})$ = NATO near infrared green envelope, which is superimposed onto Fig. 16.11.

Similar requirements are laid down for camouflage for use in desert regions. The UK uses a disruptive pattern of two colours, brown and beige. The brown must achieve a NIR reflectance value of 45 ± 5%, and the beige a value of 65 ± 5% between 1.0–1.2 μm.

16.9.5 Dyes for near infrared camouflage

Cellulosic fibres and blends thereof have been successfully dyed with a selected range of vat dyes which have large conjugated systems of aromatic rings. These have met NATO requirements for many years.[35] Other fibres such as wool, and synthetic fibres such as nylon, polyester, aramids (Nomex®, Conex® or Kermel ®), and polyolefins have proved more difficult, since these fibres are dyed with small molecules which have either little or no absorption, and thus high reflectance, in the NIR region.

Many vat dyes have been specifically developed for the express purpose of NIR camouflage, and many patents appear in the literature.[37] They tend to be based upon large anthraquinone–benzanthrone–acridine polycyclic ring systems. They possess very high light, rub, and wash fastness on cellulosic materials, as well as resistance to chemical agents. Many sulphur dyes also exhibit NIR control, but have poor light and wash fastness. They are precluded from military use because of their corrosive interaction with materials used for bullet and shell casings, and detonator compositions. Until recently, it was necessary to incorporate strongly IR absorbing pigments, such as carbon black, which can be melt spun into polyester fibres such as Rhone Poulenc 'grey' polyester, which contains about 0.01% by weight of carbon. Finely divided carbon can also be mixed into printing pastes with suitable binders and applied to textiles. Such processes are difficult to control in production, and subsequent washing can remove some of the carefully metered carbon during use, causing changes in the NIR reflectance values.

Advances in dye application chemistry, funded by the UK MOD, now offer the possibility of NIR camouflage on a wider range of synthetic substrates, including nylon, polyester, aramids, polyolefins, and polyurethane elastane fibres.[38] Such treatments confer desirable properties of high rub, wash and light fastness on military textiles. Pigment printing of textiles using azoic colorants or isoindolinone residues has been reported.[37] Green and black pigments can be screen printed onto textiles in synthetic binders.

Clearly the requirements of NIR camouflage will change as advances in surveillance technology are made, particularly as observation of the battlefield at longer wavelengths, from 1.0–2.0 μm, may be possible in the future.

16.9.6 Thermal infrared camouflage waveband

The thermal or far infrared (FIR) wavebands are, militarily, defined as being from 3–5 μm, and 8–14 μm. In these two bands or 'windows' the atmosphere is sufficiently transparent to allow long range surveillance and target acquisition. Objects are detected by the heat energy they emit or reflect.

Thermal imagers have been around for many years. Early applications were in the medical field in laboratories, but more rugged and compact military systems are now available which can detect vehicles at ranges of several kilometres, and fixed facilities such as storage depots and airfields at ranges of tens of kilometres.

The relationships between energy emitted, emissivities, wavelengths, and temperatures are covered by mathematical relationships derived by Planck, Wien, and Stefan. In simplified terms these are:

$$\text{Wien;} \qquad \lambda_{max} T = \text{a constant} \tag{1}$$

where λ is the wavelength and T is absolute temperature.

$$\text{Stefan;} \qquad E = \eta \sigma T^4 \tag{2}$$

where η is the emissivity and σ is a constant.

Planck's equation relates the spectral radiant emittance of energy to wavelengths at various absolute temperatures. To simplify the mathematics, if we consider two typical military target temperatures, say 33 °C or 306 K for a human body, and 427 °C or 700 K for a typical aircraft or vehicle exhaust, we can consult Planckian curves, which give the following results:

- At 306 K the maximum emittance of radiation is at about 10 μm.
- At 700 K the maximum emittance of radiation is at about 3 μm.

Thus, at higher temperatures the emittance is at shorter wavelengths and vice versa. Therefore we need sensors to cover the range of targets adequately in both windows, 3–5 μm and 8–14 μm.

Stefan's law states that the amount of emitted radiation is proportional to the fourth power of the absolute temperature T, and the emissivity η of the material in question. Therefore, there are two things that we can do to reduce the thermal signature of targets, reduce the temperature and the emissivity of the target.

1 **Reduce the temperature of the target** – vehicles need to be designed so that hot exhaust systems are cooled by air or liquids, by insulating the hot components, or by rerouting the hot piping so that it is covered and not visible. This all adds to the cost and complexity of military vehicles.

   With human targets we can lower the thermal signature by wearing more insulated clothing, putting on covers, or increasing the external surface area using fur or pile-type structures. Unfortunately, this adds to the thermal discomfort of the individual in all but the coldest climates. Additionally, humans are reluctant to wear insulative coverings on the face, one of the most thermally highlighted parts of the body.

2 **Reduce the emissivity of the target** – emissivity is a measure of how efficiently an object radiates its energy. It has a scale of values from 1.0 for a perfect emitter, to 0.0 for materials which emit no energy at all. The list below shows typical emissivities of a range of common materials:[29]
   - Textile fabrics: 0.92–0.98
   - Sandy soil: 0.91–0.93
   - Old snow: 0.98
   - Concrete: 0.94–0.97
   - Hardwood: 0.90
   - White paint: 0.91
   - Black paint: 0.88
   - Stainless steel: 0.12
   - Aluminium: 0.04–0.09.

   Most surfaces are good emitters, except those which are shiny and metallic. Therefore, we can lower the emissivity of the target by using a shiny reflective cover, although this will obviously interfere with visual camouflage (see Section 16.4).

Practical thermal camouflage-screening materials tend to be complex laminates which include a textile fabric support in woven slit film polyolefin carrying a film of aluminium or other shiny metal foil. The foil is covered by a dull green coloured coating, which has the correct visual and NIR characteristics. The green coating is formulated so that it allows the thermal imager to 'look' through it at the underlying metal layer. Such materials have been in service for some years and are specified by UK MOD.[39] The thermal screen is used in conjunction with a standard green/brown incised camouflage net. In this form it avoids other complex thermal reactions caused by solar radiation warming the material, or reflection of radiant energy from the 'cold' (–50 °C) sky, which the imager 'sees' as a negative contrast. The thermal screen is bulky, stiff, and impermeable to sweat vapour, which precludes its use in clothing.

Current work includes studies to provide comfortable, practical thermal camouflage materials for clothing. Further speculative research is examining the feasibility of smart, adaptive camouflage using thermochromic,[40] photochromic, or electrochromic dyes, along with phase change materials. These could provide 'chameleon' type camouflage over a wide range of the spectrum.

16.10 Flame-retardant, heat protective textiles

There is a unique difference between civilian and military fire events. The majority of civilian fires are accidental events, whereas the majority of military fires are deliberate, planned events specifically intended to destroy equipment and installations, or to maim and kill human life.

Military textile materials are often the first materials to ignite. These propagate small fires leading rapidly to large conflagrations. The threat is such that defence forces have paid particular attention to the use of flame-retardant textiles for many applications. These specifically include:

- **Protective clothing** – for firefighters, bomb disposal (explosive ordnance disposal, EOD) crews, nuclear, biological and chemical (NBC) protection, AFV tank crews, naval forces aboard ships and submarines, aircrew, and special forces such as SAS (Special Air Service), SBS (Special Boat Service), and US navy seals.
- **Equipment** – such as tents, shelters, vehicle covers, and bedding.

16.10.1 Military flame and heat threat

The threats to humans and equipment are as follows:

1. open flames from burning textiles, wood, vegetation, furnishings and fuels
2. radiant weapon flash – whether conventional or nuclear weapons
3. exploding penetrating munitions, especially incendiary devices
4. conducted or convected heat, including contact with hot objects
5. toxic fumes generated in confined spaces
6. smoke which hinders escape in confined spaces, and can damage other equipment
7. molten, dripping polymers, which can injure clothed humans and spread fires in furnishings and interior fittings.

16.10.2 Severity of the military threat

Taking each of the main threats in turn will allow a worst-case threat envelope to be constructed. Table 16.14 gives details of the severity of the threat to tank (AFV) crewmen, coupled with the attendant exposure time limits to ensure survival.[41]

The worst-case envelope must therefore encompass fluxes up to 600 $kW\,m^{-2}$ normally. The nuclear thermal pulse situation is complicated, because we assume

Table 16.14 Severity of the military heat and flame threat

Threat source	Typical heat flux ($kW\,m^{-2}$)	Survival time (s)
Burning fuels	~150	7–12 s for no injury
Exploding munitions	~200	<5 s
Penetrating warheads	~500–560	<0.3 s
Nuclear thermal pulse inside closed vehicle	~600–1300	<0.1 s

that an enclosed vehicle is not in a region above its nuclear blast survivability levels. The thermal pulse may not be instantly significant, but the total heat absorbed by the mass of a vehicle may produce heating effects which cause fires inside the vehicle.

16.10.3 Criteria for protection of the individual

We must consider the following criteria to protect forces exposed to the threats listed in 16.10.1:

1. Prevent the outer clothing and equipment catching fire by the use of flame-retardant, self-extinguishing textiles. The material should still be intact and have a residual strength not less than 25% of the original. It should not shrink more than 10% after the attack.[42]
2. Prevent conducted or radiated heat reaching the skin by providing several layers of thermal insulation or air gaps.
3. Minimise the evolution of toxic fumes and smoke in confined spaces by careful choice of materials. This is mainly a hazard posed by clothing and textiles in bulk storage. The submarine environment is a particularly hazardous problem, as it relies on a closed cycle air conditioning system. Some toxic fumes may not be scrubbed out by the air purification system.
4. Prevent clothing in contact with the skin melting, by avoiding thermoplastic fibres such as nylon, polyester, polyolefins, and polyvinylidene chloride (PVDC).

16.10.4 Toxic fumes and smoke

All fires cause oxygen depletion in the immediate area of the fire, and deaths can occur if the oxygen content falls from the normal 21% down to below 6%.

All organic fuels produce carbon monoxide (CO), especially in smouldering fires where complete oxidation of the fuel does not occur. A survey[43] involving almost 5000 fatalities showed that the vast majority of the deaths were attributable to carbon monoxide poisoning. Moreover, the lethal concentrations of CO were much lower than previously believed. Another study[44] concluded that carbon monoxide yields in big fires are almost independent of the chemical composition of the materials burning.

The stable product of all combustion processes and developing fires is carbon dioxide (CO_2), an asphyxiant. It plays a major part in the complex effects which toxic products have on human organisms.

Textile fibres which contain nitrogen, such as wool, nylon, modacrylics, and aramids will produce volatile cyanide compounds to a lesser or greater extent. It has been confirmed that only 180 ppm in the atmosphere will cause death after 10 min. Whether the concentrations available from such fibres is high enough to be a significant threat in real fires is a subject for continuing debate.

Other toxic species from military textile materials include halogenated compounds from polyvinyl chloride (PVC) and neoprene-coated fabrics and PVDC fibres. A range of very toxic oxy-fluoro compounds can be released from PTFE laminates or coatings, and acrolein (an irritant) from cellulosic or polyolefin fibres. Finally, antimony compounds are used in conjunction with halogens to confer flame-retardation properties in fibres, finishes, and coatings. It is somewhat ironic that these two species confer flame-retardant properties, but at the expense of increasing the levels of toxicants in the atmosphere. Textiles used in submarines and ships are required to meet low toxicity and smoke qualification standards.

16.10.5 Thermoplastic melt hazard

There have been documented situations where forces have experienced the adverse effects of molten fibre polymer sticking to the skin of the wearer in fire and flash situations. This can cause more severe injuries in certain specific cases.

Table 16.15 shows that thermoplastic fibres have melting points as low as 105 °C and if used in underwear can shrink onto the skin prior to melting. The most commonly used fibres today are polyester (Tm = 255 °C) and nylon (Tm = 250 °C), often used in blends with cotton or other fibres.

There is a justifiable argument that the melt hazard is an academic problem, since if anyone is caught in open flames and their underwear reaches temperatures of 250 °C or more, the individual would already be severely injured by primary heat source burns. However, if we consider weapon flash burns, the situation is different, in that large amounts of energy are delivered to the clothing in a fraction of a second. There are multiple effects from a melt burn event, as follows:

1. There may be little or no 'pain alarm time' in which the individual has time to register the pain and move away from the heat source.
2. Latent heat, which is taken in when the fabric melts, is released again on resolidification. This causes more heat to be pumped into a localised area of skin.
3. Molten polymer residues shrink and stick to the skin, causing additional difficulties when medical help attempts to remove the remains of the clothing.
4. Polymer degradation products may enter broken skin wounds and circulate in the blood stream.

Research work which attempted to simulate melt burns from a range of polyester/cotton fabrics[45] concluded that there is enough energy in one molten drop of a polyester-rich blend with cotton to cause skin burns, if it were to fall on unprotected skin. Burns occur from all blends containing more than 35% polyester. The report concluded that the cotton component in the blend can absorb some of the molten polymer, and that the problem can be avoided if blends containing less than 35% polyester are utilised.

Table 16.15 Thermoplastic textile fibres

Fibre type	Trade names	Melting point (Tm°C)
Polyester	Terylene, Dacron, Trevira, Thermastat, Coolmax, Patagonia	255
Polypropylene	Meraklon, Leolene, Ulstron	150
Polyamide	Nylon 6, Nylon 6–6, Tactel	250
Poly Vinylidene Chloride	Damart Thermolactyl, Rhovyl	Shrinks 95 Melts 105
Modacrylic	Teklan, SEF, Velicren	175
Spandex (Elastic Fibres)	Lycra, Vyrene	250

The melt hazard issue is still a cause for much debate, especially in its inferences for infantry and marines operating in cold climates. Some nations ignore this potential problem, whilst others, including the UK, observe the risk in certain special situations for all aircrew, tank crew, and all naval action clothing. The UK has recently relaxed the restrictions on the use of thermoplastic textiles in certain cold weather operations.

16.10.6 Flame-retardant textiles in military use

Although the range of flame-retardant products is large, the actual number of types used by military forces is quite small. Table 16.16 shows those which are used and the applications. The most widely used of these is Proban®-treated cotton, a tetrakis hydroxymethyl phosphonium hydroxide product, bound to the fibre and cured in ammonia. Its advantage is its wide availability and low cost. It provides a finish which is resistant to many (careful) launderings, and gives good protection with low thermal shrinkage in a fire. Its disadvantages are that it liberates fumes and smoke when activated, the treatment can weaken the fabric or spoil its handle, and it must not be laundered using soap and hard water, as these can leave flammable residues in the fabric.

The use of Proban in naval action dress (shirt and trousers) is in a blend with 25% polyester, which improves appearance and durability. The Royal Navy action coverall is a two-layer Proban cotton garment in antiflash white, and it is worn in conjunction with Proban-treated white knitted headover and gloves during high alert action states on board ship.

The meta-aramid fibres possess good physical durability, low toxicity and low smoke evolution properties. However, their high cost limits their use to the special

Table 16.16 Flame-retardant textiles in military use

Fibre/fabric type	Treatment type	Cost	Military uses
Proban cotton	Chemical additive	Relatively cheap	Navy action dress Navy action coverall Anti-flash hood and gloves Air maintenance coverall Welder's coverall
Aramid	Inherent fibre property	Expensive	Tank crew coverall Aircrew coverall Bomb disposal suit Submariner's clothing Arctic tent liners
Zirpro wool	Chemical additive	Medium/ high	Navy firefighters RAF firefighters Foundry workers
Modacrylic	Inherent fibre property	Medium/ low	Nuclear, biological, and chemical clothing Tent liners
Flame-retardant viscose	Chemical additive	Medium	In blends with aramid fibres only

end-uses listed in Table 16.16. They are available in a wide range of fabric types, invariably in blends with para-aramids, or flame-retardant viscose.

Wool treated with colourless hexafluoro-titanium or -zirconium complexes (Zirpro®) treatments are used for certain heavy firefighter's clothing fabrics, such as the navy 'Fearnought' coverall, and the RAF ground crew coverall. These are typically heavy felted-type fabrics of weights in excess of $1000\,g\,m^{-2}$, which provide good thermal insulation properties for high risk duties.

All UK fighting forces in navy, army and airforce would have to go to full scale war wearing a two-layer oversuit with boots and gloves to protect them from nuclear, biological, and chemical (NBC) warfare threats. The outer fabric is currently a woven twill with a nylon warp and modacrylic weft. The modacrylic component provides a limited degree of flame and flash protection (see Section 16.12).

The general service military tentage material currently consists of a polyester/cotton core-spun base fabric which is coated with a mixture of PVC and PVDC resins with antimony oxide as a flame inhibitor.[46] It also contains pentachlorophenyl laurate (PCPL) as a rot-proofing agent, although this is in the process of change, owing to the adverse effects of PCPL on the environment. Future tentage materials may be made from wholly synthetic polyester-coated textiles which do not require rot proofing. Coatings made from specially formulated PVC, polyurethane, or silicone polymers may be used. There are currently a range of neoprene and hypalon rubber-coated nylon and polyester fabrics which are used for flame-retardant covers, inflatable decoys, and shelters.

Finally, the exotic polybenzimidazole (PBI) fibre has been used in US aircrew clothing and UK military firefighters have recently been equipped with clothing made from PBI Gold fibre.

16.11 Ballistic protective materials

Most military casualties which are due to high speed ballistic projectiles are not caused by bullets. The main threat is from fragmenting devices. In combat, this means, in particular, grenades, mortars, artillery shells, mines, and improvised explosive devices (IEDs) used by terrorists. Table 16.17 shows statistics for casualties in general war, including World War II, Korea, Vietnam, Israel, and the Falklands conflicts.[47]

The main cause of injury to civilians (including police officers) has been bullets. These can be classed as 'low velocity' bullets fired from hand guns (revolvers, pistols) at close range. 'High velocity' weapons, such as rifles and machine guns tend to be used at longer ranges. Generally speaking, the velocity itself is less important than the kinetic energy, bullet shape, or composition of the bullet.[47] In terms of lethality, however, bullets are more likely to kill than bomb fragments, which will tend to

Table 16.17 Cause of ballistic casualties in general war

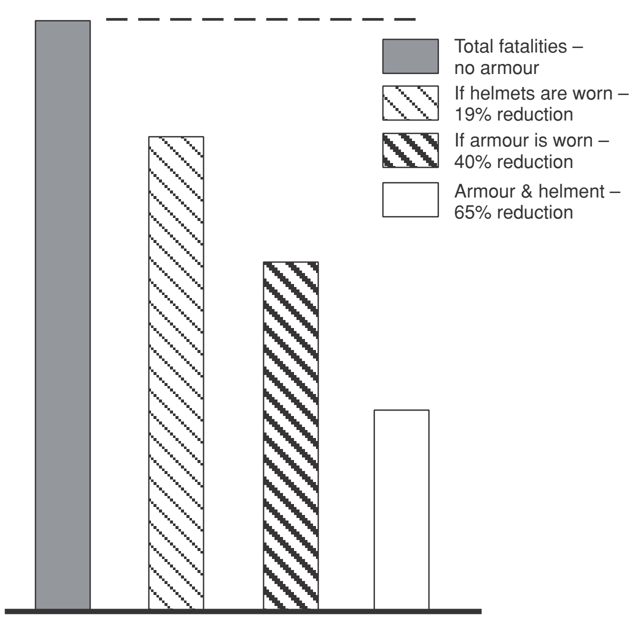
Cause of casualty	Percentage
Fragments	59
Bullets	19
Other	22

inflict several wounds, ranging in severity, depending on the source and distance of the blast. There may also be casualties from the secondary effects of bombs, including collapsing buildings, exploding aircraft, sinking ships, and flying debris.

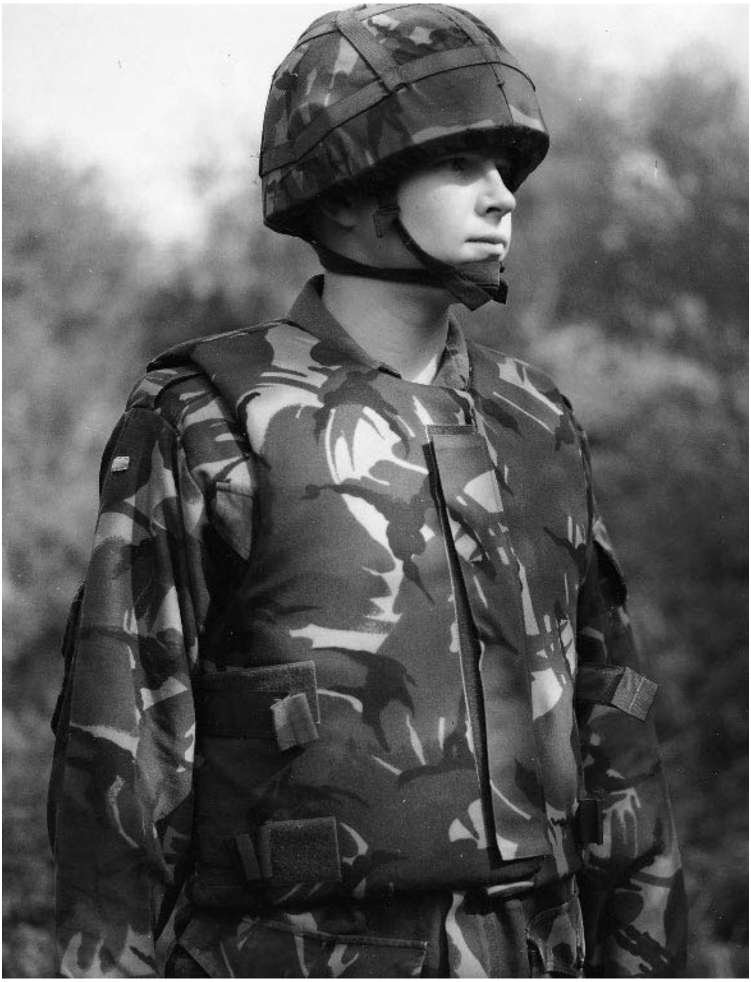
16.11.1 Levels of protection

Providing the appropriate level of protection for an individual is rarely a problem. The limiting factors governing protection are related to the weight, bulk, rigidity and thermophysiological discomfort caused by body armour. Given these restrictions, it is apparent that textile structures should be prime candidates to provide the low weight, flexibility, and comfort properties required. Textile body armours may give protection against fragments and low velocity bullets, but not against other threats such as high velocity bullets of, typically, 5.56 mm, 7.62 mm and even 12.7 mm calibre. Textile armours are also defeated by flechettes, which are small, sharp, needle-shaped objects, disseminated in large numbers by exploding warheads or shells. In the case of these high speed projectiles we have to resort to using shaped plates made from metals, composites or ceramics. These are placed over the vital organs such as the heart. Figure 16.12 shows the reduction in casualties which result from wearing various levels of body armour and helmets. It is clear that the more a person wears, the better are the chances of avoiding injury. There does, however, seem to be a law of diminishing returns operating here owing to the bulk and weight factors mentioned earlier. For all the reasons stated here, ballistic protection of the active individual is always a compromise.

To illustrate the compromises that have to be made, the lightest fragment protective combat body armour (CBA), covering the minimum area of the body might



16.12 Estimated reduction in casualties resulting from wearing body armour (troops standing in the open, threatened by mortar bomb.)

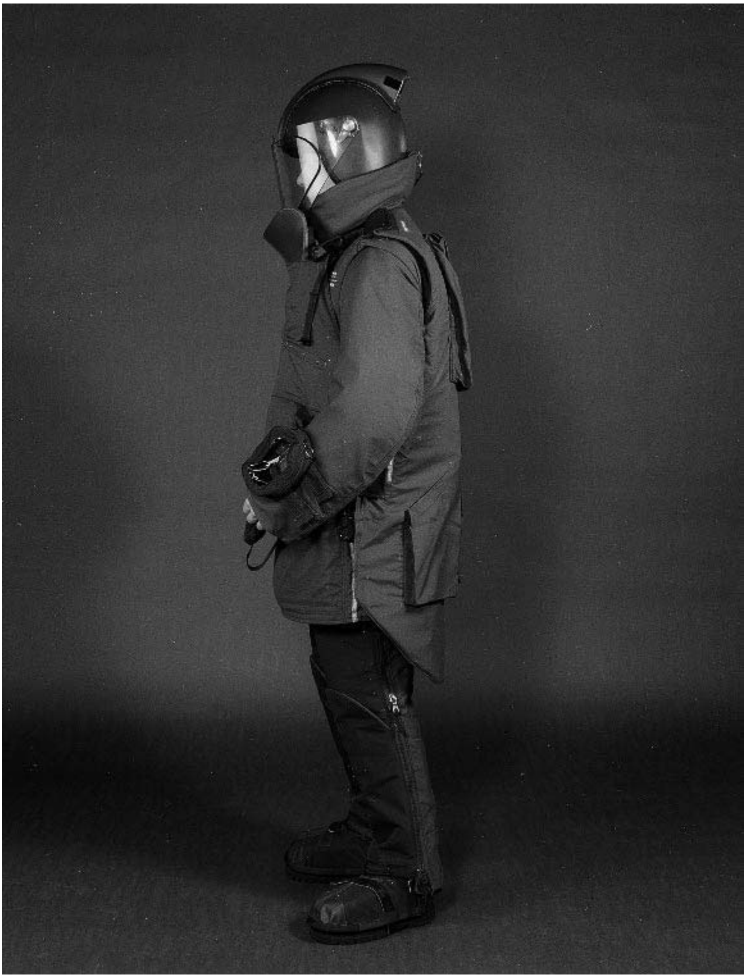


16.13 Soldier wearing combat body armour.

weigh 2.5–3.5 kg (see Fig. 16.13). If we then provide additional protection against high velocity bullets, using rigid plates and increasing the area of torso coverage, the weight might conceivably reach 13–15 kg, or about one-fifth of the weight of an average fit adult, and this does not include helmets, visors, and leg protection![48] The ultimate clothing system for whole body and head protection is the EOD suit, which is shown in Fig. 16.14.

16.11.2 Textile materials for ballistic protection

Ballistic protection involves arresting the flight of projectiles in as short a distance as possible. This requires the use of high modulus textile fibres, that is those having very high strength and low elasticity. The low elasticity prevents indentation of the body and subsequent bruising and trauma caused by the protective pack after impact. Woven textiles are by far the most commonly used form, although non-woven felts are also available.



16.14 Explosive ordnance disposal clothing.

One of the earliest materials used was woven silk, and work done in the USA has examined the use of genetically engineered spiders silk to provide protection. High modulus fibres based on aliphatic nylon 6-6 (ballistic nylon), have a high degree of crystallinity and low elongation, and are widely used in body armours and as the textile reinforcement in composite helmets.[49]

Since the 1970s a range of aromatic polyamide fibres have been developed (para-aramids). These are typically based on poly-para benzamide, or poly-para phenylene terephthalamide. Fibres with tradenames such as Kevlar® (Du Pont) and Twaron® (Enka) are available in a wide range of decitexes and finishes.

A range of ultra high modulus polyethylene (UHMPE) fibres have been developed. They are typically gel spun polyethylene (GSPE) fibres, with tradenames such as Dyneema® (DSM) and Spectra® (Allied Signal). Fraglight® (DSM) is a needle felt fabric having chopped, randomly laid GSPE fibres. These GSPE fibres have the lowest density of all the ballistic fibres at about $0.97\,g\,ml^{-1}$. The main disadvantage of these fibres is their relatively low melting point at about 150 °C. Research

Table 16.18 Comparison of ballistic textile performance against steel wire

Property	Steel wire	Ballistic nylon	Kevlar 129	Dyneema SK60
Tensile strength (MPa)	4000	2100	3400	2700
Modulus (MPa)	18	4.5	93	89
Elongation (%)	1.1	19.0	3.5	3.5
Density ($g\,ml^{-1}$)	7.86	1.14	1.44	0.97

work on the formation of composite materials for helmets using these polyethylene fibres has indicated that excellent ballistic performance was possible with significant reductions in areal density of about 45% compared with ballistic nylon.[50,51] Table 16.18 is a comparison of the properties of these synthetic fibres with steel wire.

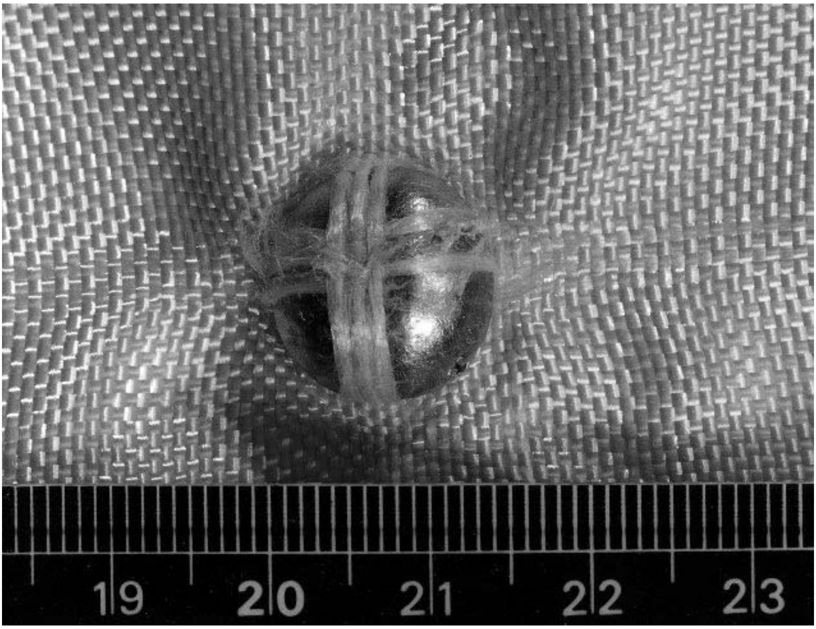
It is clear that these specialist textile fibres offer the great advantages of low density and high tenacity compared with steel wire. Para-aramids and polyethylene fibres have demonstrated the vast improvements in performance which are possible with these fibrous polymers.

16.11.3 Fabric types and compositions

The majority of ballistic fabrics are of a coarse loose plain-woven construction. Continuous multifilament yarns with the minimum of producer twist tend to give the best results. The loose woven construction produces a light flexible fabric ideal for shaped clothing panels. However, with a loose sett there is a high probability of a projectile sliding between the individual filaments. In addition, a certain amount of bulk is necessary, as ballistic resistance increases with overall areal density. This necessitates the use of many layers, typically between 5 and 20, to produce a ballistic pack which will perform adequately. Figure 16.15 shows the inner layer of such a pack at the point where a bullet or fragment has been arrested. Each body armour layer is allowed to move independently, the pack is secured by stitching quilting lines or squares to maintain a degree of flexibility. This allows the wearer to bend, turn, and make arm movements. It is necessary to seal the ballistic vest inside a waterproof and light-tight cover, as the presence of moisture and UV light can reduce the ballistic performance.

16.11.4 Ballistic testing and evaluation

Material packs are tested in instrumented firing ranges. It is necessary to fire a projectile of standardised weight and size, and at a range of velocities, which are aimed at the pack. Using these fragment-simulating projectiles in a series of test firings enables a measure known as the V_{50} for each material pack and projectile to be made. The V_{50} is the velocity (in $m\,s^{-1}$) at which there is an expected probability of penetration of 0.5, that is, 50% go through and 50% do not. This can be used as a quality control measure. We also need to know the V_0, which is the highest velocity at which no penetration occurs at all. This is sometimes known as the V_c or critical velocity. The V_c is thought by some to be a more practical measure, since the objective of the armour is to stop all projectiles reaching the wearers body!



16.15 Ballistic pack showing arrested bullet.

In order to judge how effective a protective armour is likely to be in combat, we have to use a model which simulates a combat situation. The initial information fed into the model includes the V_0 for several sizes of fragment against a particular armour, together with the area of body coverage. We then use data about real weapons ranged against unprotected versus protected individuals. This casualty reduction analysis enables us to predict the real effectiveness of the armour in reducing casualties and fatalities.

16.12 Biological and chemical warfare protection

Biological and chemical warfare is a constant world threat. The toxic agents used are relatively easy to produce and their effects are emotionally and lethally horrific to the general population. They are weapons of insidious mass destruction. The fact that they have not been used in recent conflicts may be due, in part, to the difficulty of delivering and disseminating such weapons onto specific chosen targets. It is imperative to avoid adverse meteorological effects, such as wind blowing the agents back onto the delivering force! There is also the deterrent effect, as the use of such weapons may invoke massive escalating retaliation with other means of mass destruction, such as nuclear weapons.

The types of classic agent which might be used are outlined in Table 16.5. Perhaps one of the most common is mustard agent, which attacks both moist skin, tissues and the respiratory system, causing severe blistering, swelling and burns. Normal mustard agent is bis-(2-chloroethyl) sulphide, which was first produced in 1822, but first used in the later stages of World War I.

The nerve agents were first developed in the 1930s by German chemists,[52] and are so called because they affect the transmission of nerve impulses in the nervous system. They are all organophosphorus compounds such as phosphonofluoridates and phosphorylcyanides which are rapidly absorbed by the skin and respiratory system, although they are primarily respiratory hazards. They were given names such as Tabun (GA), Sarin (GB), and Soman (GD). Agent VX was developed by the USA in the late 1950s, and is one of the most toxic and persistent agents known.[53,54]

The borderline between biological and chemical agents has become less clear over the years as developments in biotechnology have multiplied the types of agent now possible. Classical biological agents would include bacteria, viruses, and rickettsia, but we can now include genetically modified forms of these, and add other toxins, peptides, and bioregulators.

The primary and essential devices for protection of the individual are ori-nasal or full-face respirators which are designed to filter out and deactivate the toxic species. However, mustard agents attack the skin, and nerve agents can be absorbed by damaged skin and at pressure points such as fingers, knees and elbows, necessitating the use of full body protective clothing, Most current clothing systems use activated carbon on a textile substrate to absorb the agent vapour. Activated carbon can be used in the form of a finely divided powder coating, small beads, or in carbon fibre fabric form. This form of carbon has a highly developed pore structure and a high surface area, enabling the adsorption of a wide spectrum of toxic gases. Those with boiling points greater than 60 °C are readily physically adsorbed on the charcoal, but vapours boiling at lower temperatures must be chemically removed by impregnants supported on the carbon.[55]

In practice most nations carry the activated charcoal on an air-permeable nonwoven support, on a foam-backed textile, or in a laminate consisting of two textile fabrics sandwiching a charcoal layer. The UK uses a nonwoven, multifibre fabric onto which is sprayed charcoal in a carrier/binder.[56] This fabric is treated with an oil- and water-repellent finish. The charcoal layer is used in conjunction with an outer woven twill fabric consisting of a nylon warp and modacrylic weft, and carries a water-repellent finish. This layer wicks and spreads the agent to attempt to evaporate as much as possible before it transfers to the charcoal layer underneath (see also Section 16.10.6).

NBC protective clothing is currently worn over existing combat clothing, and is cumbersome and uncomfortable to wear in active situations. Much development work is devoted to attempting to reduce the thermophysiological load on the wearer, by reducing the number or bulk of layers in the clothing system whilst maintaining a high level of protection.

References

1. GEORGE WASHINGTON, *Speech to American Congress*, 8th January 1790.
2. C S BROWN, 'Benjamin Thompson – Count Rumford', *MIT Press*, 1995, p. 128.
3. M CHAPPELL, *The British Soldier in the 20th Century, Part 1, Service Dress 1902–1940*, Wessex Military Publishing, Hathersleigh, Devon, 1987, p. 3.
4. M CHAPPELL, *The British Soldier in the 20th Century, Part 6. Tropical Uniforms*, Wessex Military Publishing, Hathersleigh, Devon, 1988, p. 3.
5. M G BURNS, 'British combat dress since 1945', *Arms and Armour Press*, Classell, London, 1992, pp. 6, 7, 15.
6. M CHAPPELL, *The British Soldier in the 20th Century. Part 5. Battledress 1939–1960*, Wessex Military Publishing, Hathersleigh, Devon, 1987, pp. 8–16.
7. G T HOLMES, Paper presented at 8th Commonwealth Conference on Clothing and General Stores, Department National Defence, Canada, 1965.

8. Defence Standard 00-35, Issue 2, *Environmental Handbook for Defence Materials*, Chap. 1-01, Table 2, MOD Directorate of Standards 6, March 1996, p. 5.
9. R F GOLDMAN, 'Biomedical effects of underwear', *Handbook on Clothing*, ed. L Vangaard, Chap. 10, NATO Research Study Group 7, Natick, Massachussetts, USA, 1988.
10. N R S HOLLIES, 'Comfort characteristics of next-to-skin garments', Proceedings of International Seminar on Taxtiles for Comfort, Shirley Institute (BTTG), Manchester, 1971.
11. K H UMBACH, *Clothing Physiology – Tasks and Problems*, Vortrag VIII, UNIDO-Chemiefaserkurs, Wien, 1981.
12. ISO 11092. (DIN 54101). Measurement of stationary thermal and water vapour resistance by means of a thermo-regulatory model of human skin, 1993.
13. Specification UK/SC/4919, *Vest and Drawers, Cold Weather, Olive*, UK MOD, DCTA, Didcot, Oxon, November 1986.
14. C E MILLARD, D M KELM and A J ROBERTS, *An Assessment of Various Types of Cold Weather Underwear*, Centre for Human Sciences Report DRA/CHS/PHYS/95/045, Oct. 1995.
15. A HOBART and S HARROW, *Comparison of Wicking Underwear Materials*, Defence Clothing and Textiles Agency Report, January 1994.
16. M F HAISMAN, 'Physiological aspects of protective clothing for military personnel', *Clothing Comfort*, eds. N R S Hollies and R F Goldman, Ann Arbor Science, Michigan, 1977, Chap. 2, p. 5.
17. C COOPER, 'Textiles as protection against extreme winter weather', Textiles, 1979 **8**(3) 72–83.
18. R A SCOTT, *Efficiency of Thermal Insulation Materials*, unpublished work, Defence Clothing and Textiles Agency (DCTA), Colchester, UK, 1985.
19. B.S 4745: 1971 'Measurement of Thermal Insulation using a Guarded Hotplate Apparatus'.
20. R A SCOTT, 'Effect of moisture on thermal insulation materials', unpublished work, DCTA, Colchester, 1985.
21. N A GASPAR, 'Technical problems associated with protective clothing for military use', Paper presented at 36th International Man-made Fibres Conference, Osterreichisches Chemiefaser Institut, Dornbirn, Austria, 17–19th September 1997.
22. R A SCOTT, 'Coated and laminated fabrics', in *Chemistry of the Textile Industry*, ed. C M Carr, Blackie Academic and Professional, 1995, pp. 234–243.
23. C HIGENBOTTAM, *Water Vapour Permeability of Aircrew clothing*, MOD, DERA Report PLSD/CHS5/TR96/089 of December 1996.
24. G R LOMAX, 'Hydrophilic polyurethane coatings', J. Coated Fabrics, 1990 **20** 88–107.
25. M DRINKMANN, 'Structure and processing of Sympatex® laminates', J. Coated Fabrics, 1992 **21** 199–211.
26. N C GRAY and C E MILLARD, *Moisture Vapour Permeable Garments – a Physiological Assessment*, DERA, Farnborough Report PLSD/CHS5/CR96/010 April 1996.
27. D CONGALTON, 'Thermal and water vapour resistance of combat clothing', paper presented at *International Soldier Systems Conference*, Colchester, UK, ed. R A Scott, MOD, Defence Clothing and Textiles Agency, October 1997, 389–404.
28. Courtaulds Ltd, *Courtaulds Countersurveillance System*, Brochure FSM 92616c/9, 1992.
29. A F VICKERS, *Camouflage – What the Eye Can't See*, MOD, DCTA Lecture to Physics Department, Durham University, November 1996.
30. NATO Standardisation Agreement (STANAG) 2835, 'NATO UVR White Colour – Reference Curve and Limit Curves/Colorimetric Tolerances and Characteristics', edition 2, September 1995.
31. T NEWARK, Q NEWARK and J F BORSARELLO, *Brasseys Book of Camouflage*, Brasseys, London, 1996.
32. Y A IVANOV and B V TYAPIN, *Infra-red Technology in Military Matters*, English translation AD 610765, Air Force Systems Command, Wright – Patterson Air Force Base, Ohio, USA, published by Brasseys, London, 1965.
33. M A RICHARDSON, I C LUCKRAFT, R S PICTON, A L RODGERS and R F POWELL, '*Surveillance and Target Acquisition Systems*', Brasseys Battlefield Weapons and Systems, Technology Vol. VIII, Brasseys, London, 1998.
34. J FABIAN, H NAKAZUMI and M MATSUOKA, 'Infra red photography', *Chem. Rev*. 1992 **92** 1197.
35. Ciba-Geigy Ltd., *Dyes for Infra-Red Camouflage*, CIBA, Basle, Switzerland, 1972.
36. NATO STANAG 2338 'NATO Green Camouflage Spectral Curves – Visual and Near Infra-Red Requirements', now published as Defence Standard 00-23, Ops. 5, Glasgow, Oct. 1980.
37. S M BURKINSHAW, G HALLAS and A D TOWNS, 'Infra-red camouflage', Rev. Prog. Colouration, 1996 **26** 47–53.
38. S M BURKINSHAW, P J BROWN, 'Dyed materials', US Patent 5,607,483 dated 4th March 1997, Secretary of State for Defence.
39. Specification UK/SC/5154, *Cloth, Camouflage, Low Emissivity*, MOD, DCTA, UK, October 1992.
40. D AITKEN, S M BURKINSHAW, J GRIFFITHS and A D TOWNS, 'Textile applications of thermochromic systems', Rev. Prog. Textile Colouration, 1996 **26** 1–9.
41. NATO AC/301 Group on Standardisation of Material and Engineering Practices (B5), Allied Combat Clothing Publication no. 2, 12 November 1992.
42. S F ELTON, 'UK research into protection from flames and intense heat for military personnel', Fire and Materials, 1996 **20** 293–295.

43. S M DEBANNE, M M HIRSCHLER and G L NELSON, 'The importance of carbon monoxide in the toxicity of fire atmospheres', *Fire Hazard and Fire Risk Assessment*, ASTM STP 1150, ed. M M Hirschler, Amer. Soc. Testing & Materials, Philadelphia, 1992, 9–23.
44. M M HIRSCHLER, S M DEBANNE, J B LARSON and G L NELSON, 'Carbon monoxide and human lethality', *Fire and Non Fire Studies*, Elsevier, London, 1993.
45. R A J STAPLES, *The Melt/Burn Hazard from Cotton/Polyester Materials*, S&TD Tech. Memo 96/10, MOD, DCTA, Colchester, October 1996.
46. Specification UK/SC/4436, *Cloth, Duck, Cotton and Polyester, NATO Green, IRR, Flame, Water and Rot Resistant*, UK, MOD, Nov. 1991.
47. L TOBIN, *Military and Civilian Protective Clothing*, MOD, DCTA lecture given to RMCS Wound Ballistics course, January 1994.
48. A L MARSDEN, *Current UK Body Armour and Helmets*, MOD, DCTA lecture 1994.
49. R G SHEPHARD, *The Use of Polymers in Personal Ballistic Protection*, MOD, DCTA lecture, 28 November 1986.
50. A G ANDREOPOULOS and P A TARANTILI, 'Corona treatment yields major advantages', *Textile Month*, February 1997, 30–31.
51. S S MORYE, P J HINE, R A DUCKETT, D J CARR and I M WARD, *A Preliminary Study of the Properties of Gel Spun Polyethylene Fibre-based Composites*, UK, MOD, DCTA lecture, Personal Armour Symposium, Colchester, Essex, Sept. 1996.
52. A HAY, 'At war with chemistry', *New Scientist*, 22 March 1984, 12–18.
53. U IVERSSON, H NILSSON and J SANTESSON (eds.), *Briefing Book on Chemical Weapons*, No. 16, Forsvarets Forskningsanstalt (FOA), Sundbyberg, Sweden, 1992.
54. A HAY, S MURPHY, J PERRY-ROBINSON and S ROSE, 'The poison clouds hanging over Europe', *New Scientist*, 11 March 1982, 630–635.
55. B TUCKER, 'Protection and Decontamination in Chemical and Biological Warfare', *J. Defence Sci. (DERA)*, HMSO, 1997 **2**(3) 280–283.
56. Specification UK/SC/3346G, *Cloth, Bonded, Multi-Fibre Anti-gas*, MOD, DCTA, QPS, Didcot, Oxon., Sept. 1982.