CHAPTER 7

# Nonapparel Coating

## 7.1 SYNTHETIC LEATHER

A footwear material primarily protects the feet from the environment in which it is worn. Leather is preferred as a footwear material because it has certain desirable properties such as high moisture absorption as well as high air and moisture vapor permeability. The removal of liquid perspiration by evaporation and absorption makes a leather shoe more comfortable to wear. The stretchability of leather makes it suitable for the lasting process, in the manufacture of the shoes. The waterproofness of leather is not adequate. A coating to make it waterproof makes it impermeable. Leather can be given different finishes, viz., patent, grain, and suede.

The search for synthetic leather has been catalyzed due to periodic shortages of leather and for economic considerations. Moreover, natural leather comes in different sizes and thickness, thus it cannot be handled by automatic, computer-controlled production lines. Synthetic substitutes are now increasingly in use for various footwear components like shoe uppers, linings, insole, insole covers, stiffeners, etc. A UNIDO report predicts that in the near future, only 60% of shoe material will be leather, and the rest will be alternate materials. Ideally, a man-made shoe upper material should have a similar appearance, with mechanical and physical properties comparable to natural leather. Synthetic materials for footwear applications are generally coated fabrics. These may be compact coated impermeable fabrics or breathable fabric/poromerics.

### 7.1.1 COMPACT COATED FABRICS

In the quest for a low cost alternative to leather as a material for shoe, upholstery, and other applications, vinyl-coated fabrics have been considered the most suitable material. The flexibility of the product can be adjusted by varying the plasticizer content, and a leather-like appearance can be given by embossing. The initial PVC fabrics were nonexpanded coatings on closely woven fabrics.

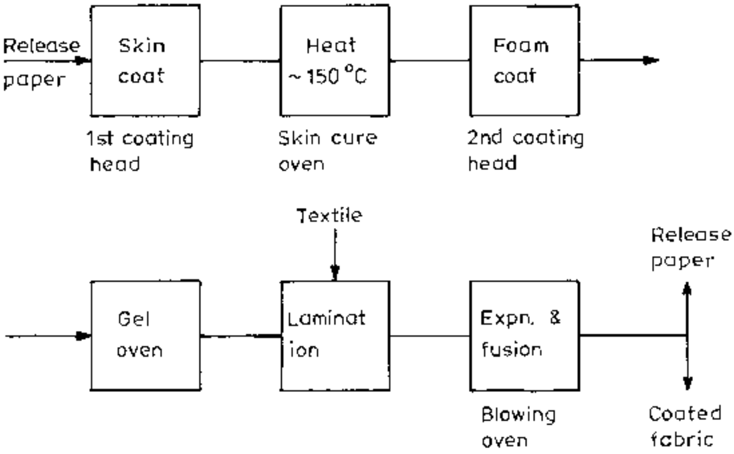

**Figure 7.1** Flow diagram for the production of expanded vinyl.

These fabrics are stiff, lack the handle of leather, and are difficult to upholster. Besides, they tend to harden and crack quickly due to migration of the plasticizer. These fabrics typically have a thick skin coat ~190 $g/m^2$ on plain weave cotton base fabrics of ~150 $g/m^2$. They find use as upholstery material in less expensive outdoor furniture [1,2].

In the 1950s, expanded vinyl-coated fabrics were developed, which had handle and drape properties very similar to leather. Expanded vinyl fabric consists of knitted fabrics as the base material, an intermediate layer of cellular PVC, and a wear-resistant top coat [1,3]. These fabrics are also known as leather cloth and are produced by transfer and calender coating. In the transfer coating process, a thin coating of plastisol is applied on a release paper or steel belt. This top coat is partially fused at about 150°C. A second coat of plastisol containing 1–5% blowing agent is then applied on the top coat. This layer is again partially fused, laminated to fabric, and then subjected to complete expansion and fusion at about 200–230°C (Figure 7.1). The temperature of the oven depends on the nature of the blowing agent. A glossy top surface can be obtained by applying an acrylic precoat prior to casting the top coat. Embossing can be achieved by using embossed release carrier.

In the clandering process, vinyl sheeting containing a blowing agent is produced in the normal manner. The sheet is then laminated to a wear layer and fabric. The composite layer is then heated in an oven at high temperature (~200°C) to activate the blowing agent to produce the foam layer [4]. A cross section of the various layers of expanded vinyl is shown in Figure 7.2.

Upholstery grade cloth has a thick foam layer ranging from 360–480 $g/m^2$, a top layer of 180 to 360 $g/m^2$, embossed to a leather-like grain and a knitted base fabric of ~100 $g/m^2$. Expanded vinyls are lower in cost and have better

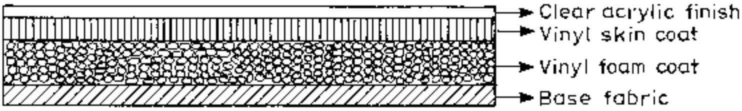

**Figure 7.2** Layers of expanded vinyl.

durability than leather. They have, however, a cool feel, undergo cracking due to plasticizer migration, and cannot be dry cleaned [2].

Polyurethane-based fabrics are superior to vinyl-coated fabrics in leather simulation, durability, and low temperature flexibility. These fabrics contain a knitted base fabric, a polyurethane foam middle layer, and a wear resistant top coat similar to the expanded vinyls [3]. The method of their manufacture is also similar. A top coat of PU is cast on a release paper in the transfer process. This is followed by a coating mixture of polyol, isocyanate prepolymer, and a blowing agent. The composite is then foamed, cross-linked, and laminated to a textile base. The foamed imitation leather is then separated from the release paper [5].

Both expanded vinyl and polyurethane-based leather cloth are widely used for upholstery, soft luggages, handbags, shoes, seat covers, and door panels of cars, etc. [1,3]. An important requirement of upholstery fabric is that it should have proper flame retardant additive to reduce the ignitability of the products, smoke generation, and toxicity of the decomposition products [6].

The vinyls have a very low water vapor permeability. The PU-coated fabrics, because of their hydrophilic nature, have some water vapor permeability $\sim$5–18 $g/m^2/h$, but the same is not adequate enough for comfort properties of shoe materials [7].

### 7.1.2 POROMERICS

These are second generation synthetic leathers and are so named as they contain porous polymers. Besides aesthetics, they have certain other important characteristics:

*a.* A microporous structure
*b.* Air and water vapor permeable
*c.* Water repellent on the outer decorated side

These properties render poromerics as a shoe upper material having properties in between leather and vinyl-coated fabrics, because all the properties of leather have not been achieved in poromerics as yet.

The most prevalent method of manufacturing [7–9] poromerics is to incorporate a soft porous polymeric mass in the fabric matrix and subsequently coat it with a porous polymeric layer. The porous polymer is obtained by coagulation of a polymer solution in a nonsolvent. The polymer most suited for the purpose is polyurethane. Typically, a solution of polyurethane in dimethylformamide (DMF) is applied on a fabric, by dipping and/or coating, followed by dipping in a large excess of water. The polyurethane coagulates in the nonsolvent due to precipitation and coalescence. On drying, the microporous polymeric material is obtained that imparts both waterproofness and water vapor permeability to the fabric. DMF is used as a solvent for polyurethane because of the following:

- It is a good solvent for PU.
- It has a high boiling point, so it does not readily evaporate from solution.
- It is highly miscible in water. Water can therefore permeate into the DMF solution, bringing about coagulation.

The textile materials used as backing are generally nonwoven fabrics that may be nonreinforced or reinforced with knitted or woven fabric. Nonreinforced nonwoven has poor strength and higher permanent set. Fabrics in woven form are also used in the form of raised pile, however, they suffer from inferior ductility. The fiber properties, particularly its strength, water absorption, and fineness, are important parameters determining the final properties of the end product. Fine fibers, particularly microfibers, give excellent aesthetics comparable to those of leather [10]. The structure of a poromeric with nonwoven backing material resembles that of leather, the microporous top coat and the backing are comparable to the grain and reticular layers of leather. Poromerics can also be obtained by transfer coating on a release paper followed by coagulation and lamination of the microporous film onto a fabric such as in Porvair.

#### 7.1.2.1 Coagulation Process [5,11]

A completely reacted polyurethane solution of about 20% in case of nonwovens or about 10% for a woven substrate is mixed with aqueous pigment, ionic polyurethane (to promote coagulation), and a polyelectrolyte. The solution is deaerated prior to use. The steps involved in the manufacture are varied depending on the manufacturer, but a typical flowchart is given below. The fabric is initially impregnated with the PU solution by coating or dipping, followed by coagulation in a water bath, and excess water removal by squeezing. To the moist PU impregnated substrate, a coating of polyurethane is applied by knife coating. Steam is then passed over the fabric for gelling and to initiate coagulation. The fabric is then dipped into a coagulation bath containing 15–35% DMF in water. After coagulation, the fabric is washed in water bath, followed by washing in suction drums, where DMF is removed and recovered. The wet fabric is next dried in a tenter (Figure 7.3).

The pores of the polymer are of micron level and are interconnecting, leading to permeability. Various factors control microporosity and other properties of the poromerics [7,9].

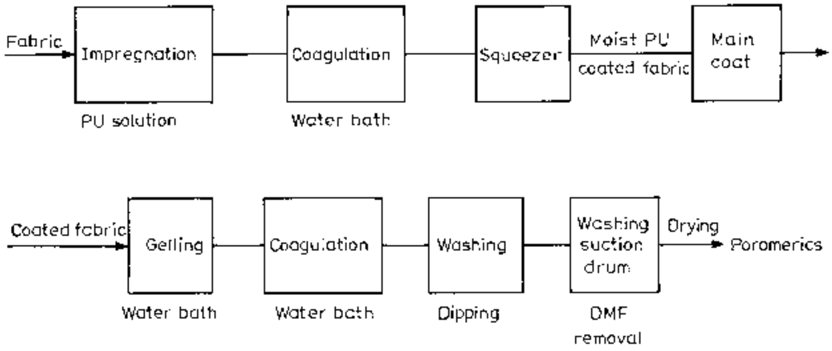

**Figure 7.3** Flow diagram of manufacture of poromerics by coagulation.

(1) The type of polyurethane and the additives
(2) Viscosity and solid content of the solution
(3) Type of fabric
(4) Extent of impregnation
(5) Concentration of DMF in bath and temperature of coagulation
(6) Total dip time and extent of squeezing
(7) Washing efficiency
(8) Drying conditions

A variation of the process is the incorporation of water-soluble [5,7] salts like sodium chloride or ammonium sulphate into the PU solution. During coagulation, the salts leach, forming a controlled pore structure. Microporous polymer can also be obtained by dissolving polyurethane into a volatile solvent (THF) and a high boiling nonsolvent (a hydrocarbon solvent). On evaporation, the volatile solvent leaves behind polyurethane in the nonsolvent, leading to precipitation of the polymer and coagulation. The microporosity depends on the quantity of the nonsolvent. A process of coating fabric with porous PU from PU dispersion has been developed by Stahl-Holland [10]. A fabric is impregnated and coated with aqueous polyurethane dispersion. Precipitation and coagulation is done at an elevated temperature above 93°C, using hot water, steam, or microwave. The end product containing porous polymer has much better leather-like properties. The process is nontoxic and requires a simpler production unit.

### 7.1.2.2 Poromerics from Prepolymers [5]

The coagulation process described above uses fully reacted polyurethane. Two methods of manufacture of poromerics from prepolymers have been

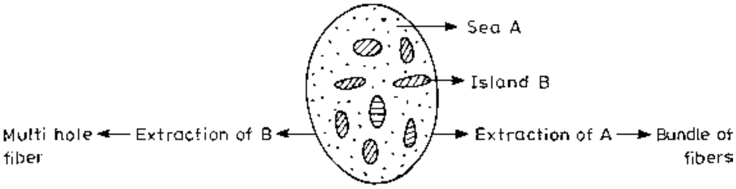

**Figure 7.4** Structure of special fiber of Clarino. (Adapted with permission from *Encyclopedia of Chemical Technology,* Vol. 14, 3rd Ed. 1979, © John Wiley & Sons [7].)

reported in the literature. They are polyaddition in solution and dispersion. In the former, prepolymer is dissolved with chain extender in a solvent or solvent mixture in which the end product is insoluble. As the reaction proceeds, the polyurethane formed becomes less soluble with time and precipitates out, occluding the solvent. On evaporation of the solvent, a poromeric is obtained. In the dispersion process, isocyanate prepolymer is dispersed in a solvent, (aromatic hydrocarbons) nonsolvent (water) mixture. To this emulsion, the chain extender is added. Polyaddition occurs during evaporation of the solvent mixture, leaving behind a porous polymeric structure.

The dried fabric containing coagulated PU is then finished by a thin spray coating and embossing in a calender, to impart the desired color and grain for leather-like appearance. Suede-like appearance is obtained by buffing.

A number of brand products of poromerics are available in the market [7,8,12]. They differ in the coating as well as in the textile backing. For instance, Porvair is a microporous film laminated to a fabric substrate, whereas Clarino (Kuraray) contains coagulated polyurethane in a fiber matrix with a top coat of microporous polyurethane. Nonreinforced nonwoven fiber matrix has been used in Clarino. For this purpose, special fiber has been developed by Kuraray that is close in properties to collagen [13]. Two immiscible polymers are melt spun to give a fiber of a cross section shown in Figure 7.4. It has been termed as island and sea fiber where one polymer is dispersed in another polymer matrix. By selective solvent extraction of either the dispersed phase (island) or the matrix (sea), a hollow supple multihole fiber or a bunch of fine denier fiber results. The use of these fibers leads to a product of considerably enhanced suppleness. Contemporary man-made leather such as Sofrina (Kuraray) and Ultrasuede (Toray) employ microfibers of less than 0.3 denier for the nonwoven matrix to obtain excellent properties resembling leather [7].

A cheaper alternative to poromerics [9] is obtained by applying a top coat of conventional coating of polyurethane by the transfer process, on a fabric substrate already impregnated with porous polyurethane by the coagulation process. This method has much better aesthetics, handle and appearance, and seam holding properties than compact PU-coated fabrics but poorer permeability than poromerics. These fabrics are extensively used in Europe for ladies footwear.

### 7.1.2.3 Structure of Porous Films

The structure of porous films formed by the coagulation process and the effect of various additives have been studied by Chu et al. [14]. They have noticed a dense skin layer on top of a spongy base layer. The base layer consists of finger-like cavities and large cavities. Cellulose acetate membranes used for the desalination process are made by a similar coagulation process using acetone-solvent and water-nonsolvent and have similar porous structure. The reasons of formation of such a structure of the cellulose acetate membranes have been intensively investigated [15–17]. The top skin layer is formed either by the evaporation of the solvent or by rapid precipitation at the outermost surface. As the water diffuses through the skin layer to the precipitation zone, the rate of coagulation slows, and coarser precipitate is formed. Thus, the pore size increases from top to bottom. Similar reason can be attributed to the pore structure of porous polyurethane. The effect of additives studied by Chu et al. [14] are sodium nitrate, water, and defoaming agents. Addition of sodium nitrate and water in the PU-DMF solution accelerates the coagulation process and promotes formation of larger cavities in the base layer. Antifoaming agents such as Span-60 and octadecanol, which are hydrophobic in nature, lower precipitation rate. Dense skin layer is formed with Span-60, and finger-like cavities are absent using octadecanol. It has also been found that temperature of the coagulation bath plays an important role in pore size formation. A cold bath produces a small poromeric structure throughout the entire coating; a warm bath creates a small structure at the surface and a large pore structure underneath. The reason for this is the heat of solution generated when DMF and water are mixed. If the bath is cold, it has the ability to absorb this heat without significant temperature rise. The polymer-rich layer then coagulates quickly, resulting in a small pore structure. If the bath is warm, the water-rich layer penetrates more deeply into the precipitation layer before the polymer cools to the point that it will coagulate. This gives rise to a large pore structure. The other important factor in pore size development is the concentration of DMF in the water/DMF bath. A high DMF concentration yields a large pore structure.

## 7.1.3 POROUS VINYLS [18]

These materials are used as liners in footwear for absorption of moisture. They are much cheaper than PU-coated fabrics and poromerics. There are various techniques to produce these materials:

(1) Incorporation of soluble material into the plastisol matrix, calendering it into sheet form, leaching the soluble material to produce voids, and then laminating it on to fabric
(2) Foaming (chemical or mechanical)

(3) Sintering—careful heating and pressure sinters solid vinyl particles, generating a solid containing voids

Murphy [18] has described a novel and improved process of manufacturing absorptive vinyl. The process consists of coating a fabric with plastisol containing noncompatible thermoplastic polymer particles. During fusion and gelling, the incompatible thermoplastic softens and shrinks, as it has no adhesion with the vinyl matrix. By controlling the size and content of particles and by applying mechanical stress, it is possible to create interconnecting tunnel-like voids. The absorptive vinyl is laminated to a backing material of natural-synthetic fiber blend and finished. Absorptive vinyls have high moisture absorption and desorption rates and are particularly suited for liner applications using impermeable uppers.

### 7.1.4 PTFE LAMINATE [19]

GORE-TEX® is a hydrophobic polytetrafluoroethylene film containing micropores. It repels water but permits passage of water vapor. A triple laminate with an outer layer of textured nylon fabric, a middle layer of GORE-TEX® film, and an inner layer of knitted fabric can be used as a shoe upper. Total ingress of water is prevented by sealing rather than stitching the seams for construction of the shoe. These uppers are used for applications where a high degree of water repellency combined with breathability are required.

## 7.2 ARCHITECTURAL TEXTILES

The use of shelters made of textile material for protection against the elements dates back to mankind's earliest days. Over the years, different types of tents have been developed to meet various requirements of the military, explorers, nomads, etc. These tents are made of cotton canvas with wax emulsion treatment to provide water repellency. The development of high strength, rot proof, hydrophobic synthetic fibers along with improved polymer coating has given an impetus in the use of coated fabric as a membrane material to envelope very large building structures of the size of stadia or airports.

The fabric envelope is capable of resisting the elements of weather such as wind, rain, snow, sunlight, and even biological degradation. Although lower cost transparent film can be used as a membrane material, it lacks durability. Coated fabrics are the most widely used material because of high strength and environmental resistance. The advantages of these fabric envelope buildings are summarized below [20,21].

- The coated fabric envelope is much lighter than conventional building material (may be 1/30th) requiring much less structural support and reinforcements. This reduces the cost of the building.

- It provides large obstruction-free spans, suitable for large gatherings.
- The construction time is much shorter.
- Smaller envelopes can be dismantled and reerected elsewhere.
- Fabric envelopes are better resistant to natural hazards like earthquakes.

### 7.2.1 MATERIALS

The fiber and the fabric requirements of the coated fabric envelope are quite stringent. They should have the following properties:

*a.* High strength, to withstand the tension applied during construction of the structure, weight of the suspended fabric, and stresses due to wind, rain, and snow
*b.* The fiber should be creep resistant and have high modulus, for dimensional stability and resistance to deformation.
*c.* Retention of mechanical property in widely varying temperature conditions
*d.* Resistant to water, sunlight, and atmospheric pollutants
*e.* Long life
*f.* Low cost

The cost factor eliminates high-performance fibers such as aramids and carbon fibers. The choice is thus restricted to high tenacity polyester and glass fiber, out of which polyester is more popular. Continuous filament yarns are preferred over staple yarns because of higher strength and resistance to extension. The twist level is kept low to prevent fiber slippage and yarn rupture. Usually, woven structures are preferred for rigidity and dimensional stability. The type of weave should be such as to produce good yarn packing to minimize fabric deformation under tension and to provide a certain level of resistance to water and wind penetration. Generally, plain weave and 2 × 2 basket weaves are used. The high tenacity polyester fabrics used for architectural purposes have been categorized into a few fabric types, with fabric weight ranging from 220 to 630 $g/m^2$. A typical fabric is made of 1000 d yarn in plain weave (9.5 × 9.5 ends × picks/cm) having a weight of 220 $g/m^2$ [20,22].

The coated fabrics are orthogonally anistropic, i.e., they elongate differently in warp and weft directions. This aspect is to be taken care of in designing textile structures. Weft inserted warp knit and multiaxial knits have been tried to achieve isotropic structures, but they have not been successful, because on coating, the former develops anisotropy, and the latter results in a very stiff material [22].

Glass fabric has high strength, resists stretching, does not wrinkle, does not burn, and has high reflectivity, keeping the interior of the structure cool.

The polymer used for coating or laminating, the architectural fabric, should impart certain important properties to the membrane fabric. These properties are as follows [20,23].

- waterproofness
- impermeability to air
- resistance to abrasion and mechanical damage
- resistance to weathering and pollution
- ability to transmit and reflect light (It should have adequate translucency to provide natural illumination in daylight hours.)
- weldability
- flame retardance

Such requirements are met by two polymers, they are PVC and polytetrafluoroethylene (PTFE). Coating is preferred to lamination because laminated fabrics tend to delaminate on repeated flexing and wind lashing. Because of the high sintering temperature of the polymer, PTFE can only be applied on glass fabric. Two materials have found success as membrane material for envelope, PVC-coated polyester and PTFE-coated glass fabric [20,21,24]. A third material, silicone-coated glass fabric, is also emerging as a material of choice.

PVC-coated fabrics exhibit a dirt pick up problem, which is usually minimized by applying a thin top coating of polyurethane or acrylic lacquer. White is considered the color of choice, because the high reflectivity reduces surface temperature and enhances service life [3]. Translucency of the fabric is achieved by controlling the yarn density and by properly formulating the PVC compound. PVC-coated fabrics are easily joined by welding and are easier to handle for construction of the structure. A disadvantage of PVC is its slow embrittlement due to gradual loss of plasticizer. However, a properly designed fabric has a life of over 15 years. Different grades of these fabrics are available in the trade to meet the varying load-bearing capacities. The fabric weight ranges from 600 to 1000 g/m$^2$. These fabrics, because of their inherent flexibility, are suitable for semipermanent structures that may be taken down and reerected on a new site [20,22,25].

PTFE-coated glass fabric has several advantages. The polymer is chemically inert, self-cleaning, highly resistant to weathering, inherently translucent, and has excellent flame retardant properties. There are, however, certain problems in using this fabric. The abrasion resistance of PTFE is poor, the fabric is brittle causing handling problems, and joining of the fabric panels is difficult. The abrasion resistance is improved by incorporating glass filler in the outermost layer of the coating. The brittleness of glass fabric is reduced by a finishing treatment. Hot-melt PTFE resin is used for joining the fabric panels. Different grades of fabric are available with fabric weight ranging from 1250 to 1450 g/m$^2$. The fabrics have a solar reflectance of about 70% and transmission of about

15%. In view of the durability and stiffness of the fabric, they are used for permanent structures, that have a life of over 20 years [23].

### 7.2.2 STRUCTURES

Structures using coated fabric envelopes can be classified into three main types. They are tents, air inflated structures, and tensile structures. As stated earlier, wax-emulsion-treated canvas has been in use as tent cover for a long time, however, they have now been replaced by PVC-coated polyester. In a tent, the fabric is draped on a frame and is not tensioned. In large structures, the fabric is tensioned by air inflation or cables [20].

#### 7.2.2.1 Air Supported Structures and Shelters

In these structures, the fabric assembly that serves as the roof is anchored and sealed to a ground foundation. Air is pumped inside to inflate and tension the envelope (Figure 7.5). The pressure required is only 3% above the ambient, therefore, it does not affect the comfort of the occupants. The entrance and exit doors are air locked to minimize drop of pressure when opened. Any fall of pressure is automatically corrected by pumping in air by a compressor. A double-layer roof is used to provide thermal insulation. Air houses were initially developed for protection of radar antennae and telecommunication equipment from high velocity winds and weather. The material used for radomes are neoprene- or hypalon-coated glass for transparency to electromagnetic

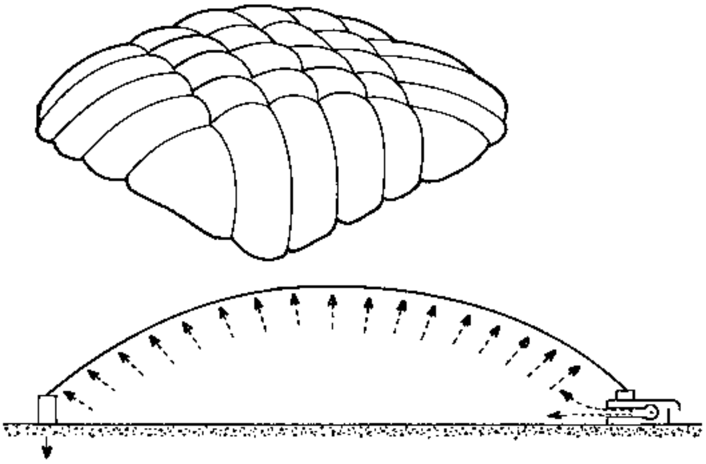

**Figure 7.5** Air-inflated structure. (Adapted with permission from R. J. E. Cumberbirch. *Textiles,* Vol. 16, no. 2. 1987 © Shirley Institute, U.K. [21].)

radiation. Air supported buildings are now used for sports halls, exhibition halls, mobile field hospitals, storage bases, swimming pools, etc. For these purposes, the fabric widely used is PVC-coated polyester. These types of buildings are very stable, because highly flexible fabric distorts to distribute the damaging load due to strong winds and returns to the original shape after the wind has abated. The response to wind buffeting can be changed by varying the internal pressure using an automatic control system related to wind speed [21,24,25].

Another way of supporting the membrane structure is to use air beams. Air beams are convex, air-inflated (30–70 kPa) support tubes, which can be up to 1 m in diameter. They are mainly used by the military as lightweight shelters [20].

#### 7.2.2.2 Flexible Barrier Storage System

Defense equipment and weapon systems, if left unprotected from weather, while not in operation, may undergo corrosion and microbiological degradation due to uncontrolled humidity and condensation of moisture due to temperature fluctuation. This may lead to operational failure and delays in reactivation of the equipment. Preservation by surface coatings such as paint and grease is not a long-time solution. After extensive experimentation, it has been found that the equipment could be preserved indefinitely in a controlled humidity between 30–40% relative humidity.

Flexible barrier storage systems are used by defense forces for preserving military equipment like tanks, helicopters, aircraft, and weapon systems from corrosion, rot, mildew, insects, dust, pollutants, and UV degradation. The equipment is mounted on a baseboard and is completely covered by reusable flexible barrier or shroud. Proper sealing is done by zip fasteners and Velcro to make the enclosure airtight. The cover is connected to a portable, solid desiccant-type dehumidifier through a flexible duct. Dehumidified air is circulated in the enclosure to maintain a relative humidity between 30–40%. There is no pressure difference between the inside and the outside of the envelope. Inspection windows and visual detectors are provided to monitor the relative humidity inside. An alarm system is also available in case the RH alters from the desired value. Several hardware systems can be connected to a single dehumidifier by a manifold. With this system, the equipment can be preserved for very long periods and can be reactivated in a very short time, enhancing the operational efficiency. Another major advantage is the flexibility of choice of storage sites. An alternative to the dehumidification process is to evacuate the enclosed envelope. However, with the vacuum system, it is difficult to maintain 30% RH continuously. Besides, the barrier material clings to the object forming creases leading to rupture and air leakage. A flexible barrier system showing protection of a tank is shown in Figure 7.6.

The barrier material should be lightweight, strong enough to resist environmental stresses, waterproof, flame retardant, and should have low water vapor

**Figure 7.6** Flexible barrier system for protection of tank. Courtesy M/S Arctic India Sales, Delhi, India.

permeability, below 1.2 g/24 h/m$^2$. Different materials are used in the trade, they are butyl and PVC-coated nylon or polyester fabric. However, calendered multilayered PVC film is also used. The life of a shroud is between 7–9 years.

#### 7.2.2.3 Tension Structures

In these structures, metal pylons or frames and tension cables are used to support the fabric. The fabric is tensioned by cables attached to the fabric by clamps. The tensioned structures are curvilinear and may be paraboloid or hyperbolic-paraboloid in shape. The curvature and prestress due to tensioning resists externally applied loads. To maintain rigidity and stability of the structure, multidimensional tensioning with properly designed curvature is required. These structures are used for permanent buildings and use generally PTFE-coated glass fabric [20,21,24].

Major challenges in the construction of these structures are their rigidity and stability to high velocity winds, rain, and snow. The designing, therefore, requires a knowledge of textile, engineering, and architecture. There are about 150 structures all over the world, which have been erected within the last two decades. These include airport terminals, stadia, and department stores. The largest being the Haj terminal building at Jeddah International Airport for which about 500,000 m$^2$ of PTFE glass fabric was used. These buildings have a distinct structural identity, the diffuse natural light through the roof is gentle to the eye

TABLE 7.1. Properties of Awning Fabrics.

| | Types | | | |
|---|---|---|---|---|
| Properties | Vinyl-Laminated or Vinyl-Coated Polyester Backlit | Vinyl Coated Cotton | Acrylic-Painted Polyester/Cotton | 100% Acrylic Woven |
| 1. Base fabric | Polyester | Cotton | Polyester/cotton | Solution dyed acrylic or modacrylic |
| 2. Coating / finish | Vinyl/acrylic | Vinyl | Acrylic | Fluorochemical finish |
| 3. Wt, g/m$^2$ | 540–740 | 500 | 400–450 | 300–330 |
| 4. Width, cm | 155–180 | 78 | 78 | 155 |
| 5. Colors, top | Several solids | Several solids and stripes | Several solids and stripes | Several solids and stripes |
| 6. Colors, underside | White/clear | Pearl gray | Pearl gray | Same as top |
| 7. Opacity | Translucent | Opaque | Opaque | Opaque |
| 8. Backlit translucency | Yes | No | No | — |
| 9. Durability, years | 5–10 | 5 | 5 | 5 |
| 10. UV resistance | Yes | Yes | Yes | Yes |
| 11. Mildew resistance | Yes | — | — | Yes |
| 12. Water repellency | Yes | Yes | Yes | Yes |
| 13. Flame retardancy | Yes | Yes | No | Modacrylic—yes<br>Acrylic—no |

Compiled from Reference [26].

and gives a delightful ambience. The high translucency and strong membranes could one day permit games like soccer to be played under cover on real turf. Development work is going on to construct membrane structures to aid crop production in desert regions [20,24].

### 7.2.3 AWNINGS AND CANOPIES

These are architectural projections of a building. They provide shade, weather protection, decoration, and a distinct identity to the building. Awnings are wholly supported by the building to which they are attached by a lightweight rigid or retractable frame over which awning fabric is attached. Canopies are supported from the building as well as from ground. Illuminated or backlit awnings offer high visibility to commercial buildings. This is achieved by attaching lighting to the frame beneath the fabric cover. The awning and canopy fabrics are similar, however, backlit awnings are more translucent. Some of the desirable properties of awning fabrics are as follows [20]:

- resistance to ultraviolet radiation
- flame retardancy
- mildew resistance
- cleanability

From the various types of commercially available awnings listed in the "Awning fabric specifiers guide," it is seen that the major types of fabrics used for awning and canopies are as follows:

- vinyl-laminated or vinyl-coated polyester-backlighting
- vinyl-coated cotton
- acrylic-painted cotton or polyester cotton
- 100% acrylic woven

Out of these, vinyl-laminated or vinyl-coated polyester-backlighting is the most popular. Some important features of these classes are given in Table 7.1.

## 7.3 FLUID CONTAINERS

The low permeability of certain polymeric coatings have made coated fabrics a material of choice, as lightweight flexible containers for both gases and liquids. The containers for gases are known as inflatables and are meant to provide buoyancy. The liquid containers are used as storage vessels for fuels, water, etc. [27].

### 7.3.1 INFLATABLES

These are designed to contain air or carbon dioxide and are meant for buoyancy applications. One of the important uses of inflatables are in lifesaving aids such as in life jackets and in emergency rafts. Life jackets can be inflated by air, or automatically by carbon dioxide cylinder in case of an emergency. The buoyancy is properly designed so that the wearer is held in correct position in water. Modern life rafts are designed with capacities of 40 persons. They have tubular multiple buoyancy chambers, so that they remain afloat even if accidentally punctured. Emergency life rafts are inflated in seconds, by solid/liquefied carbon dioxide. All the rafts are fitted with canopies for protection against weather. The canopy usually has a fluorescent orange color for easy detection. The floor of the raft should be watertight and provide insulation from seawater. These rafts are made from nylon fabric (130 g/m$^2$), coated on both sides with polyurethane. Some naval rafts use nylon laminates containing an intermediate layer of butyl rubber, which has low permeability to gases [27,28].

Inflatable crafts are used also for patrol duty by the Coast Guard or for leisure. They are inflated by air at pressure between 15 to 25 kPa and may be propelled by oars or a small overboard motor (Figure 7.7). The air cushion of a hovercraft is also contained in a coated fabric skirt fitted around the hull at a pressure of 3 kPa. The lift to the craft is propelled by a downward air flow.

An interesting application of an inflatable is for constructing temporary bridges for ferrying heavy military vehicles across a river or pond. This is

**Figure 7.7** A motorized raft. Courtesy M/S Swastik Rubber, Pune, India.

done by laying a set of floats across the river. The floats are air inflatable buoys, containing tubular, multiple buoyancy chambers made of coated fabric. A typical float fabric is a flexible composite, consisting of two layers of nylon fabric with neoprene coating in the intermediate layer as well as on both outer layers. The weight of base fabric and coated fabrics are $\sim$240 g/m$^2$ and $\sim$1500 g/m$^2$, respectively. Other applications of inflatables include oil booms to contain oil slicks in the sea and air bags for manipulation of awkward heavy objects over water in offshore industries. Deflated air bags are used in the salvage operation of sunken objects, like crashed aircraft from sea by inflation [27,28].

Hot air balloons for leisure are also inflatables that are made of lightweight nylon fabric (30–60 g/m$^2$) in rip-stop construction, coated with a thin layer of PU to reduce porosity. However, due to the temperature of hot air inside ($\sim$100°C), UV exposure and manhandling, the fabric can last for only 300–500 flight hours [28].

The main components of inflatables are (a) coated fabrics, usually calendered; (b) the adhesive; and (c) the inflation valve. The factors that are to be considered for designing inflatables, particularly crafts for marine applications, are as follows [29]:

(1) Strength of the coated fabric: the inflatables may be considered as a thin-walled cylinder. The strength requirement of the inflatable is obtained from the hoop stress, exerted due to pressure of inflation; i.e., $pD/2t$ (where $p =$ pressure, $D =$ diameter of the tube, and $t =$ thickness), along with a suitable safety factor. Usual inflation pressure is about 15–20 kPa. The strength of the coated fabric, tensile and tear, is obtained from the textile substrate and depends on type of yarn and construction. Normally, nylon or polyester woven fabrics are used.

(2) The polymer coating: this is dependent on the type of use and life expected. The polymers generally used are neoprene, hypalon, and polyurethanes.

(3) Airtightness: the polymeric coating should be pinhole-free for proper gas holding properties.

(4) Resistance to weathering and UV degradation: this is required as the inflatables are used outdoors for very long periods.

(5) Resistance to abrasion: a higher resistance to abrasion is required for protection against damage due to launches and landings on sandy and rocky shorelines.

(6) Resistance to oil and seawater: these are important requirements as the crafts are used in marine and oily environments.

(7) Flexibility: the fabric should retain its flexibility over a wide range of temperatures ($-30$ to 40°C). Low temperature flexibility down to $-45$°C is required for rafts inflated by solid carbon dioxide.

The coated fabrics for inflatables are produced by calendering or spreading. However, calendering is more suitable for compact, thick polymeric coatings on heavy-duty base fabric. The coated fabric, which usually has a width of $\sim$150 cm, is cut into panels of various shapes depending upon the shape of the finished article. The edges of the fabric to be adhered are buffed and joined by a cold curing adhesive to form the inflatable structure. The adhesive should have certain important characteristics. They are compatibility with the polymer, good green tack, rapid cure, resistance to oil and water, and appropriate cure strength.

### 7.3.2 LIQUID CONTAINERS

Coated fabrics are particularly suitable for collapsible storage containers and for transporting liquids by land and sea. Dracone barges, which are large flexible containers, are suitable for towing liquids on the ocean. One of the latest applications of these are in pollution control due to oil spillage in the sea. The spilled oil is contained by a boom system placed around the slick. The oil is then pumped into dracones and transported away for reclamation or incineration. Dracones can also be used to transport the large quantity of detergent required to disperse the oil spill [27]. Collapsible containers are used as fuel tanks for military aircraft and as fuel containers in temporary air fields. The coated fabric can be heavy, about 5000 g/m$^2$ on a nylon base fabric of about 600 g/m$^2$. The polymer used is generally neoprene. However, for storage of fuels, nitrile rubber is used, and an approved grade of PU is used for storage of drinking water [28].

A detailed investigation has been reported to find out the parameters of weave construction by which tear resistance of base fabric used for large collapsible fuel tanks ($\sim$200 kl) could be maximized. High-tenacity nylons of 840 d and 1050 d were woven into plain, twill, and basket weave designs with different yarn densities. Considering both tear resistance and dimensional stability, a $11 \times 11$ ep/pp cm, $2 \times 2$ basket-weave fabric, constructed with 1050 d yarn gave best overall performance [30].

## 7.4 TARPAULINS

Tarpaulins are used as covers to protect commodities from damages due to weather. In the agricultural sector, they are extensively used for protecting grain and machinery, while in the construction industry, they are used to protect building supplies like timber and wet concrete. In transportation of goods by road, they are used to cover the cargo. Traditionally, canvas covers made from heavy-duty cotton fabrics with a wax emulsion and a rot-proof treatment have been used for this purpose. However, canvas covers have now been completely replaced by 450–500 g/m$^2$ PVC-coated fabric because of their lighter weight and inherently water- and rot-proof nature. Some important properties of tarpaulins are (1) waterproofness; (2) strength; (3) tear, puncture, and abrasion resistance; (4) flexibility at a wide range of temperatures; and (5) durability.

The coated fabrics used are vinyl-coated nylon or polyester fabric with weights between 500–600 g/m$^2$ ($\sim$350 g/m$^2$ coating). For covers likely to be contaminated by fuels/oils, neoprene, hypalon, or PU-coated fabrics are used [31]. High density polyethylene woven fabrics laminated on both sides by low density polyethylene films are also being used as covers. For military use, tarpaulins should have camouflage properties as well. A desirable feature for vehicle covers is reversibility that would cater to change of terrain, e.g., from green belt to desert terrain.

## 7.5 AUTOMOTIVE AIR BAG FABRICS

Untill recently, safety belts have been the only protection for passengers in a car crash. During the last decade, air bags or inflatable restraints have gained significant importance as protection for the driver and passengers in case of a collision. The original bag was designed for head-on collision, but at present, side impact bags, knee bolsters, side curtain, etc., are available for safety in any type of crash. Because frontal collisions are a major cause of accidental deaths, air bags are being introduced as a standard item in vehicles by legislation in the U.S. Consumer consciousness coupled with legislation has resulted in rapid growth of air bags during the last decade [20,32,33].

The air bag is built into the steering wheel and the instrument panel of the car. An air bag module consists of the air bag, crash sensors, and mounting hardware. In case of frontal collision equivalent to 20 km/h against a wall, sensors set off the igintor of the inflator. Pellets of sodium azide in the inflator ignite and release hot nitrogen gas. The gas passes through a filter to remove ash and other particulate matter and inflates the air bag. A pressure of 35–70 kPa is generated. The air bag is fully inflated within 60 ms and cushions the occupant from impact. After absorbing the forward force, the air bag deflates after 120 ms [20]. The capacity of a driver-side air bag is normally $\sim$65 L, but for smaller cars, it is $\sim$35 L. Passenger-side air bags are much larger (100–300 L) [33].

The air bag fabric is made from nylon 66 because of its high weight-to-strength ratio and is preferred over polyester because of higher elongation, allowing the force to distribute widely. The driver-side air bag has an elastomeric coating to provide heat shielding and ablative protection to the fabric from the hot gases. Moreover, coating seals the fabric pores and permits precise control in the deployment of the air bag.

The coated fabric should be antiblocking, have high tensile and tear strength, good adhesion, and long-term flexibility to cyclic temperature changes between extreme cold and hot conditions ($-10$ to 120°C). Besides, the fabric should

TABLE 7.2. Neoprene-Coated Fabrics for Air Bags.*

| Nylon Yarn d | Construction Plain Weave Ends/cmx Picks/cm | Base Fabric, wt. g/m$^2$ | Coated fabric, wt. g/m$^2$ |
|---|---|---|---|
| 840 | $10 \times 10$ | 190 | 280 |
| 420 | $18.4 \times 18.4$ | 185 | 260 |

* Adapted with permission from E. T. Crouch, *Journal of Coated Fabrics,* vol. 23, Jan. 1994. © Technomic Publishing Co., Inc. [32].

be soft and smooth so as not to cause secondary abrasion or bruises and have good packageability. Untill recently, two types of neoprene-coated fabrics were used because of better environmental stability and flame retardant properties of neoprene [32]. One is a heavy fabric made of 840 d nylon and the other a lighter fabric woven from 420 d nylon. The details are given in Table 7.2.

The need to enhance the life of the air bag and further reduce the size led to the development of silicone-coated air bags. Silicones are chemically inert and maintain their properties for a long time at temperature extremes. An aging study of both neoprene- and silicone-coated fabrics was carried out at 120°C for 42 days. The elongation of the fabrics prior to aging were about 40%. After aging, the elongation of silicone-coated fabric was 32% but that of neoprene-coated fabric dropped sharply to only 8%. This has been attributed to the poor compatibility of neoprene with nylon. It is possible that chlorine in the neoprene produces an acidic environment, embrittling the nylon fabric. Another drawback of neoprene-coated material is that it should be dusted with talc to prevent self-adhesion, which creates dust in the vehicle interior following deployment of the bag. Silicone-coated fabrics are more flexible and abrasion resistant than neoprene-coated ones. Moreover, because of better durability and compatibility of silicones with nylon, a thinner coating is adequate. A silicone-coated air bag fabric made of 420 d/315 d nylon weighs only about 200 g/m$^2$. They can, therefore, be packed in smaller modules [32].

For this reason, silicone coating is rapidly replacing neoprene coating for driver-side air bags. Passenger-side air bags are made of uncoated nylon fabrics as the functional requirements are not that stringent. It is estimated that by the end of the decade, the requirement of coated air bag fabric will be between 50–75 million sq. meters, making it one of the most important growth sectors for coated fabrics both in volume and in value terms [20].

## 7.6 CARPET BACKING

A variety of fibers, both man-made and synthetic, are used as face fabric of carpets. The commonly used ones are cotton, wool, rayon, polyester, polypropylene, and nylon. The carpets are given a backcoating or a fabric backing to impart strength and durability. Three types of carpet backing are used in industry [34,35].

1. *Secondary-backed carpet:* in these carpets, a secondary backing fabric, usually jute or polypropylene, is bonded to the back of the carpet by an adhesive.
2. *Unitary coating:* this consists of a simple application of an adhesive layer on the back of the carpet without any secondary backing.
3. *Foam backing:* the back of the carpet consists of a thin cushion of foam as its integral part.

The backcoating process imparts certain important properties to the carpet, viz., tuft binding, dimensional stability, resistance to water, reduced pilling, resistance to edge fraying, etc. In order to achieve all these properties and to obtain adequate adhesion with the secondary backing, it is important to select the right adhesive.

Various materials have been used as adhesive over the years. They are natural rubber latex, SBR latex, EVA emulsion, PVA emulsion, starches, etc. Out of these, SBR latex and carboxylated SBR latex are the most widely used adhesives. SBR latex is obtained by emulsion polymerization process. For backcoating purposes, the SBR latex is formulated with certain additives. They are calcium carbonate (extender), surfactant (frothing aids), and polyacrylate thickeners for adjusting the viscosity [36].

The tuft locking and stiffness depends on the coating weight of the latex as well as on the formulation such as filler content and styrene content of the latex. The stiffness and tuft locking increases with styrene content and the add on. Increase in filler content decreases the tuft locking but increases stiffness [34].

Secondary-backed carpet is a type of carpet mainly used for residential purposes. Different methods are used for lamination of the backing jute fabric. These consist of applying an undercoat of SBR latex on the back side of the carpet and an adhesive coat on the jute surface and bonding the two fabrics in between laminating rolls. The undercoat is usually frothed by air, for better weight control, has higher viscosity (14,000–18,000 cps) and higher extender content (400–800 parts/100 parts latex). The adhesive coat has lower viscosity (9000–10,000 cps), lower extender content (300–400 parts/100 parts latex), and is unfrothed [35,36].

An important method of lamination is the pan coat, jute coat process, where the undercoat and adhesive coats are applied from pans to the carpet back and jute surface, respectively, by kiss-coating or roller-coating techniques. The coated surfaces are then bonded between press rolls and cured. In the direct-coating system which is more popular (Figure 7.8), the undercoat (frothed SBR

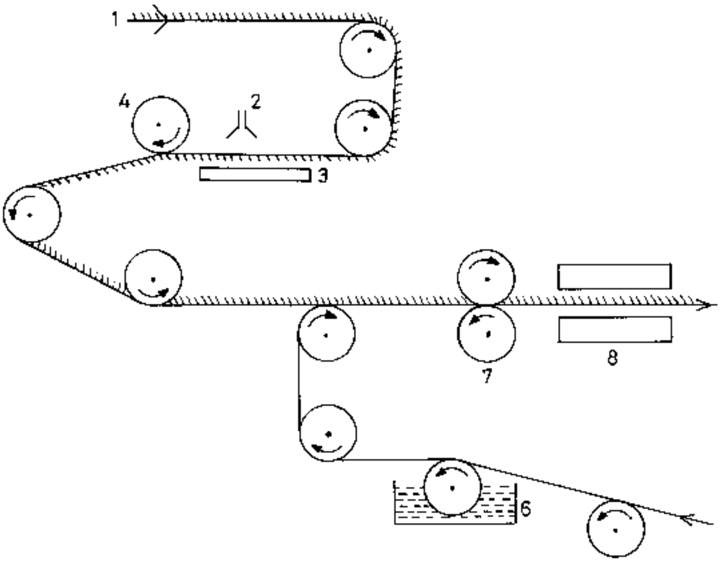

**Figure 7.8** Direct lamination of jute backing: (1) Carpet, (2) Frothed latex, (3) Bed plate, (4) Metering roll, (5) Jute fabric, (6) Adhesive, (7) Press rolls, and (8) Oven.

latex) is spread directly on the carpet back using a bed plate and a doctor roll; an adhesive coat is applied on jute surface by roller coat from pan, and the two surfaces are bonded in the usual manner [34,35].

In the unitary backing process, a layer of adhesive, usually SBR latex, is applied on the back side of the carpet by knife on roll, kiss coating, or roller coating followed by curing. As mentioned earlier, no secondary backing is used. The latex used has lower extender content (100–150 parts/100 parts of latex) and lower viscosity (7000–9000 cps). The process gives better tuft lock and dimensional stability. These carpets are used where the traffic requirement is high [34,36].

For foam backing [37], a precoat of SBR latex is first applied on the back of the carpet and dried. A foam coat is next applied by blade or roller coating. The coated fabric is then dried and vulcanized in a stenter.

Different types of foam systems based on air-frothed SBR or SBR-NR latex blend are used. In the chemical gelation system, coagulation occurs due to destabilizing the colloid, forming a rubbery continuum. Two types of gelling agents are commonly used: sodium silicofluoride, which operates at room temperature with delayed action, and ammonium salt-zinc oxide system, a heat-sensitive gellant. In a nongel foam process which is also quite popular, carboxylated latex is used along with water-soluble melamine-formaldehyde (MF) resin. Crosslinking occurs via the carboxyl groups of the latex with MF resin. The choice of the foam system depends on the technical requirements, simplicity of the process, and cost.

## 7.7 TEXTILE FOAM LAMINATES FOR AUTOMOTIVE INTERIORS

Textile fabrics are gradually replacing vinyls for car seats and interiors because of their soft handle, design color, and pattern options. The fabrics used are generally pile fabrics, of nylon or polyester. The fabric is converted into a trilaminate, comprised of face fabric, a polyurethane foam of 2–10 mm thickness, and a lining fabric. The face fabric provides an attractive look, the foam provides a soft cushioning effect, and the liner prevents the foam from wear. The most common method of lamination is flame lamination. However, laminating with dry and hot-melt adhesives is emerging as an alternative. The different methods used for lamination are discussed below [38].

### 7.7.1 FLAME LAMINATION

In this process, a roll of polyurethane foam passes over an open flame, resulting in melting of the surface of the foam, which then functions as the adhesive. This material is then bonded to fabric, by passage through nip of the laminating roll (Figure 7.9). The process is repeated for laminating the liner, on the back side of the foam.

The process is simple, does not require an oven, and gives fast line speeds. The burning of the foam, however, liberates toxic gases such as hydrogen chloride and cyanides, which have to be properly ventilated. The flame length has to be properly adjusted as large flame burns too much of the foam, while a small flame leads to insufficient melt and poor bonding. The process is restricted to foams that can be melted.

### 7.7.2 DRY ADHESIVES

Lamination can be done by scatter coating dry powder or by film adhesion of thermoplastic polymer. In scatter coating, powders of 20–200 $\mu$m of

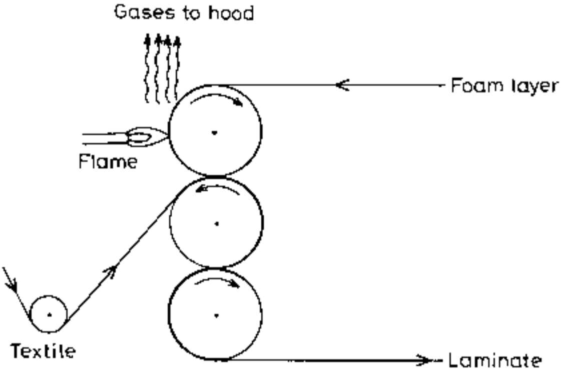

**Figure 7.9** Flame lamination.

polyester, polyamides, or EVA obtained by cryogenic grinding of polymer granules are scattered on the foam substrate. Foam containing the powder then passes through heaters to activate the adhesive by melting. The textile web is also heated to near the softening temperature of the adhesive. The lamination of the foam and textile layers is carried out by passage through nip of the laminating rolls. In film adhesion, a film adhesive obtained in roll, by melt extrusion is placed on the foam substrate, and the two layers are passed through heaters to melt the adhesive. Heated textile substrate is then laminated to the foam layer in a lamination station. The laminates are cooled prior to winding. These methods have the advantage in that no emissions are produced. They, however, require large ovens and are unsuitable for temperature-sensitive fabrics.

Adhesives can be applied on the substrate for lamination by rotogravure or by spraying processes, but the viscosity and pot life of the adhesive are constraints of their applicability.

## 7.8 FLOCKING

Flocking is the application of short fiber (flock) on an adhesive-coated substrate in vertical position. The substrate may be woven or knitted textiles, leather, paper, polymer film, etc. Flocking is used for producing a variety of items with aesthetic appeal, such as draperies, bedsteads, carpets, and artificial fur and suede. The flocking process provides an economical means of production of pile texture.

The flock commonly used in trade are nylon or viscose, 1640 d, of 0.1 to 0.6 mm length. For production of the flock, tows of fibers are extruded through the nip of rotating rolls and are cut by a blade. The speed of the rolls determines the flock length. The flock is then thoroughly washed, activated by cationic detergent, and graded prior to electrostatic deposition on the substrate. The textile substrate used are mainly woven or knitted cotton/viscose fabric. The adhesives are usually latices of NR, SBR, or aqueous dispersions of acrylics or polyurethanes. The viscosity of the adhesive is adjusted using polyacrylate thickeners to prevent strike through of the adhesive during coating.

The flocking process consists of coating the textile substrate by knife on roll, rotary screen printing, or gravure roll coating for repeat patterns. Flock is then applied on the substrate electrostatically. For this purpose, the flock fibers are introduced into a high voltage field as a result of which, as charge carriers, the fibers are transported to the adhesive-coated substrate at right angles. Adhesive-coated substrate forms the earth pole and is, in addition, vibrated by a set of rollers. The fibers that penetrate the adhesive layer are retained there, forming a dense pile. Excess flock is removed by suction, and the product is passed through a tunnel drier, which is circulated by hot air at high temperature. The product is cooled, excess flock is removed by brushing followed by suction,

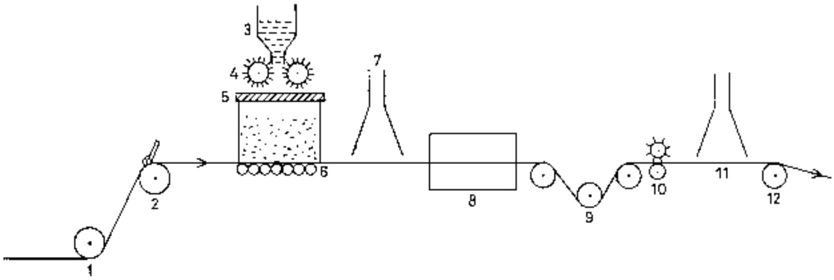

**Figure 7.10** The flocking process: (1) fabric unwind, (2) coating of adhesive, (3) hopper containing, (4) rotating brush, (5) electrostatic depositer, (6) vibrating rolls, (7) suction, (8) drying oven, (9) cooling rolls, (10) brushing, (11) suction, and (12) winding.

and it is cut into suitable lengths and packed. A schematic layout of the process is given in Figure 7.10.

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CHAPTER 8

# High-Tech Applications

## 8.1 FABRICS FOR CHEMICAL PROTECTION[2]

AWARENESS of the risks and ill effects involved in working in an environment full of pervasive liquids and chemicals has necessitated the use of protective gear for employees in the workplace and persons in public places. In the developed world, the concerns related to the ill effects of toxic chemicals are much greater compared with developing and underdeveloped countries. Nevertheless, definite and distinct awakening is taking place, and new and strict laws are being promulgated to protect individuals and the environment from the menace of toxic chemicals.

The toxicity of chemicals in general depends upon their structure, physiological action, and mode of exposure [1]. It may be safely stated that each and every chemical known to date can be considered as toxic at some level of intake. However, the most toxic chemicals developed and stockpiled for use in chemical warfare may be categorized in four classes, namely, blood agents, choking agents, vesicants, and nerve agents. Out of the above classes, vesicants and nerve agents manifest their effect through skin absorption. Vesicants damage body tisssue and form painful blisters that are difficult to heal. Nerve agents are absorbed and transported through the bloodstream where they block the enzyme acetyl choline esterase that plays a key role in the neurotransmission cycle leading to incapacitation and fatality. Coated fabrics are used for protection against these two classes of agents. Some of the important characteristics of common chemical warfare (CW) agents of concern are summarized in Table 8.1.

The toxicity and hazards associated with other common chemicals used in industries are much below the chemicals listed in Table 8.1. Nevertheless, the workers in plants and industries likely to be exposed due to the nature of the job need to be protected from their ill effects.

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[2] Contributed by V. S. Tripathi, DMSRDE, Kanpur, India.

TABLE 8.1. Properties of Important Chemical Warfare Agents.

| Name of Agent | State at 25°C | Volatility at 25°C (mg/M$^3$) | Effect | Time Taken for Appearance of Symptoms |
|---|---|---|---|---|
| 1. Pinacolyl methyl phosphono fluoridate (SOMAN) | Colorless liquid | 3060 | Nerve agent | Inhalation 1–5 min, skin 30–60 min. |
| 2. Isopropyl methyl phoshono fluoridate (SARIN) | Colorless liquid | 16400 | -do- | -do- |
| 3. Ethyl N,N′-dimethyl phosphoroamidecyanidate (TABUN) | Colorless liquid | 516 | -do- | -do- |
| 4. *o*-Ethyl-*S*-2-diisopropylamino ethyl methyl phosphonothioate (VX) | Yellow liquid | 16 | -do- | -do- |
| 5. bis-(2-Chloroethyl) sulphide (S Mustard) | -do- | 930 | Vesicant | 3 hrs. |

Coated fabrics play a key role in both civil and military applications as far as protection for the whole body is concerned. The whole gamut of coated fabrics used for protection of the human body may be conveniently classified in two broad categories, permeable or breathable and impermeable or nonbreathable. As the names suggest, the former allows free ingress and egress of air facilitating the dissipation of heat and evaporation of sweat, while the latter completely shields the wearer from the atmosphere. Obviously, the devices made of permeable-type fabrics can be used for longer duration of time due to comparatively low heat stress. However, for many applications where large quantities of toxic chemicals are handled or liquid splash may occur completely drenching the wearer, impermeable suits are preferred. Various types of permeable and impermeable coated fabrics used for protection against different chemicals and scenarios are discussed in this section.

### 8.1.1 TYPES OF CHEMICAL EXPOSURE RISKS

Chemicals can enter the human system through inhalation, ingestion, or absorption by the skin. The nature of the chemicals and the form and place of exposure decides the type of protection required. Some prominent scenarios include during war where chemical warfare agents may be used; emergencies involving accidental spills on highways; working with and handling hazardous waste; laboratory work; radioactive contamination; manufacturing operation for chemicals in pharmaceutical, electrical, and electronic industries; and in the handling of pesticides, insecticides, and herbicides. The United States Environmental Protection Agency (U.S. EPA) has classified the exposure scenarios and level of protection required in four broad categories. Coated fabrics are used for protection against skin absorption. Obviously, the use of protective clothing hampers the normal activities of the wearer, hence, a prudent

TABLE 8.2. Categorization of Exposure Scenarios and Implements Required for Protection.

| Level | Example of Scenario | Protection Implements Required for |
|---|---|---|
| A | 1. Production, storage, and packaging of extremely hazardous chemicals<br>2. War field where toxic agents have been used (damages due to inhalation and skin absorption) due to dissemination of CW agents<br>3. Decontamination drill | Full face mask, suit completely encapsulating the body, gloves and overboots |
| B. | 1. Chemicals are highly toxic if inhaled but not absorbed through the skin<br>2. Atmosphere with less than 19.5% oxygen, e.g., fire, etc.<br>3. Splash of chemicals possible | Self-contained breathing apparatus-(SCBA) Skin protection suit not completely sealed |
| C. | 1. Industrial contaminants, type and concentration known<br>2. Particulate contaminants, e.g., radioactive dust | Full face mask with appropriate canister having high efficiency particulate filter. Splash suit preventing direct contact of chemicals |
| D. | Nuisance contaminants with minimum hazards. No chemical immersion or splash | Standard work clothing and apron |

selection of chemical protective garments based on the hazard and risk of exposure anticipated is very important. Table 8.2 gives an idea of possible scenarios and the recommended protective equipment required in the given scenarios.

It may be noted from Table 8.2 that the stringent requirements of level A hazards require complete encapsulation. This drastically reduces the time of use for chemical protective clothing (CPC) made of impermeable material. In civilian applications, it is possible to rotate the deployed manpower at short intervals to finish the task. However, in military applications, especially in war field rotation, it is not possible, hence, permeable/breathable suits are preferred. CPC requirements stipulated in B, C, and D levels of hazards are not critical, nevertheless, they should provide protection against chemical splashes in B and C levels of hazards.

## 8.1.2 MATERIALS FOR IMPERMEABLE CPC

Impermeable chemical protection clothing is normally made either by barrier coating on a fabric or films as such. The fabric used for coating or as a carrier of the barrier compound provides necessary strength to the clothing. Fabrics made of polyester, polyamide, and cotton and their blends are commonly used as carrier fabrics. In disposable limited-use garments, nonwoven fabric laminated with a barrier film is preferred. The materials used for civil and military applications (against CW agents) are different, and they are discussed below.

#### 8.1.2.1 Civil Applications

Since the first use of chemicals for military purpose in World War I, tremendous advancement has taken place in understanding the barrier properties of polymeric materials vis-a-vis different types of chemicals in liquid or vapor forms. In the beginning of the 20th century, natural rubber was the only material available for coating. Prior to World War II, synthetic elastomers such as neoprene, polyvinyl chloride, and butyl rubber replaced natural rubber in civil and military CPCs. With the development of newer polymers like fluoropolymers, CPCs using a wide spectrum of elastomers, and thermoplastics were developed by leading manufacturers all over the world. Coextruded polymeric films have become a material of choice in limited-use disposable clothing. A list of different materials used in impermeable CPCs is given in Table 8.3 [2].

The criteria for selection of a material for a civil application depend on the permeation of the toxic vapor and penetration of the challenge liquid as evaluated by ASTM 739 and 903.

TABLE 8.3. Common Barrier Materials in Impermeable CPCs.

Elastomers—Unsupported/Reinforced
- butyl/bromobutyl
- chlorobutyl
- fluoroelastomers (Viton)
- urethane

Plastic Film Laminates—Coating
- chlorinated polyethylene
- PTFE
- polyethylene
- polyvinyl chloride
- polyvinylidene chloride

Bicomponent Constructions
- fluoroelastomer/butyl
- fluoroelastomer/neoprene
- PVDC/polyethylene
- neoprene/PVC

### 8.1.2.2 Military Applications

For military applications, the barrier properties are evaluated using S Mustard as the probe. This is considered the most penetrating of all the CW agents. A material is considered suitable for the protection of inanimate objects if it does not absorb more than 50% of the placed 1 $\mu$L of S Mustard on 1 cm$^2$ area of the material in 6 hrs. In personnel protection, vapor penetration should be very low because exposure to even 75 $\mu$g/m$^3$ concentration for one hour is enough to produce blisters. The test procedure of these materials is discussed in Chapter 9.

Two types of materials are used for fabrication of impermeable suits, etc.: (a) multilayer sandwich type and (b) coated nylon or polyester fabric [3]. In the former type, a barrier film of material such as polyvinylidene chloride, polyamide, or polyester is sandwiched between weldable polyolefin films. Sandwich layers are biaxially oriented before or after lamination for better mechanical strength. The overall thicknesses and weights of such multilayer films are 100 $\mu$ms and 100–150 g/m$^2$, respectively. For heavy-duty application, such as adhoc collective protection, decontamination, and disposal of munitions, coated fabrics having much higher strength than multilayer films are preferred. Butyl or perfluorocarbon rubber is used for coating, and the weight of the fabric varies between 250–500 g/m$^2$.

### 8.1.3 MATERIALS FOR PERMEABLE CPCs

Permeable fabrics allow free passage of air, permitting sweat of the wearer to freely pass out as water vapor. The advantage gained in suits made of such fabrics is significant as the physiological load in the form of heat stress is much less compared to that of the impermeable suits. It is possible to indulge in light to medium work schedules wearing these suits for a sufficient length of time.

A layer of high surface area microporous carbon (pore width <20 Å) is impregnated/coated on different carriers for attenuation of challenge concentration of the chemical agents. The role of carbon in a breathable fabric is very critical, in that, it should preferentially adsorb chemical agents with minimal desorption during usage. High surface area microporous carbon performs this task remarkably well. Desorption from micropores where adsorption forces are enhanced due to proximity of walls in slit-shaped pores is comparatively difficult. Fortunately, such active carbons are very good adsorbents of chemical agents that are adsorbed through the skin at ambient temperature. Even a bed of 0.5–1 mm of microporous carbon available in NBC fabrics provides very good protection, provided the rate of adsorption is high. Different permeable fabric systems in use globally are described below along with their salient features [3,4].

#### 8.1.3.1 Carbon-Impregnated Polyurethane Foam

Lightweight, low density, thin (1–2 mm) polyurethane appears to be good candidate matrix for impregnation of carbon. In fact, comparatively large quantities of carbon (200 $g/m^2$) can be impregnated in foam material, yet loss of carbon during work schedules and military operations is insignificant. However, the insulation properties of foam and its ability to adsorb fluids are serious disadvantages that cause a lot of physiological stress. Moreover, being voluminous material, the suits made of the carbon-impregnated foam cannot be packed in a small space. The deterioration of foam, especially in a hot and humid atmosphere, is another drawback. Suits of this type are currently being manufactured and used in France and some other countries.

#### 8.1.3.2 Carbon-Impregnated Cotton Flannel and Nonwoven Fabric

Activated carbon in very fine powder form can be coated on open-structure carriers such as cotton flannel and nonwoven fabric using a suitable binder. In the case of flannel, air permeability is on the low side. This type of carbon-coated fabric is used in China for NBC suits. Thin wadding of nylon or polyester reinforced by open-structure cotton scrim is probably the best carrier for active carbon, and this type of coated fabric gives very good air permeability. Polychloroprene is used as a binder because of its flame retardant properties. It reduces the adsorbability of carbon only marginally. The carbon content per unit area (45–80 $g/m^2$) is about one-third compared to foam-impregnated material, nevertheless, a faster rate of adsorption due to the finer particle size and better air permeability more than compensates this shortcoming. Such suits are made and used in the U.K.

#### 8.1.3.3 Bonded Spherical Carbon Adsorbents

In this system, microspheres of activated carbon having diameter 0.5–1.0 mm are point bonded on a carrier fabric. Approximately 150 $g/m^2$ carbon loading is achieved in this way, and this gives much better life when compared to carbon-coated fabrics. However, due to the larger granule size, the rate of adsorption is low, and larger quantities of carbon per unit area result in more weight, higher heat stress, and more cost. This type of microsphere-coated fabric is manufactured in Germany and the U.S. for military applications.

#### 8.1.3.4 Active Carbon Fabric (Charcoal Cloth)

Activated surface area microporous adsorbent media in a fabric form was developed by Maggs [5] using viscose rayon fabric as precursor. The manufacturing process of activated carbon fabric comprises of pretreatment of the precursor fabric with a Lewis acid solution and the carbonization and activation in a carbon dioxide atmosphere. The surface properties of the end product can be controlled by careful selection of operating parameters [6]. This type of adsorbent media can be used in protective clothing after proper lamination with woven or nonwoven fabric. The quantity of activated carbon available per unit area of fabric is quite high (100–120 g/m$^2$), and the rate of adsorption is also very high. In spite of all the advantages, poor mechanical strength of charcoal cloth has found limited use in chemical protective clothing.

## 8.2 THERMOCHROMIC FABRICS

A number of high technology fibers have been deveoped in recent years, some of them are based on microencapsulation technology [7,8]. These include fabrics that release perfume on rupture of the microcapsule (fragrance fabrics) and fabrics that change color with temperature. An example of the color-changing fabrics is Toray's Sway brand of skiwear. This is PU-coated nylon that contains microcapsules containing heat-activated dye. A ski suit can be made to change color from bright red at the slopes outside and white indoors by the side of a fire. The color-changing fabric is of great interest because it has potential application for camouflage. The dyes used in these fabrics are thermochromic in nature which change color with temperature.

Numerous inorganic and organic compounds show thermochromism, and the subject has been reviewed [9]. Inorganic compounds show both reversible and irreversible thermochromism due to phase change or due to change in ligand geometry of the metal complexes. Temperature-indicating paints showing irreversible thermochromism has been used for a long time as a warning of hot spots and as a record of heat history in the electrical and chemical industries. The inorganic compounds have not found favor in textile applications as the color change generally occurs in solution or at high temperatures. The ideal thermochromic system for apparel application should show reversible thermochromism between ambient and body temperature. Reversible thermochromism in the solid state is exhibited by many organic compounds. These compounds undergo stereoisomerism, molecular rearrangements, or are liquid crystals. Among the liquid crystals, the most important systems are cholesteric mesophase. These have limited use in textiles due to high cost, color restricted to deep shades, low moisture resistance, and low color density. Sterically hindered ethylene compounds such as bianthrone and dixanthylene also show thermochromism. These compounds are characterized by at least one ethylene group, a number of aromatic rings, and a hetero atom, usually N or O. The ethylenic bond provides a route for extension of conjugation and places restrictions on possible molecular orientation. As the temperature is increased, the molecule changes to a different stereoisomer, which is colored. These compounds show transition above their melting point $\sim$150°C, thus are not suitable for textile applications.

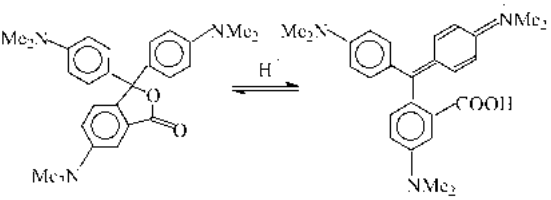

**Figure 8.1** Tautomers of crystal violet lactone.

Certain dyes undergo keto-enol type of tautomerism. Such tautomeric rearrangements can lead to an increase in the conjugation and formation of a new chromophore, leading to color development. Such rearrangements can be induced by a change of temperature, pH, or polarity of the solvent, resulting in thermochromism. These dyes are extensively used for textile applications. The most common types are fluorans, crystal violet lactones, and spiro pyrans. All of these dyes undergo ring opening rearrangements [10]. The equilibrium of crystal violet lactone is shown in Figure 8.1.

Reversible thermochromism composition is made from such dyes, along with a color developer containing acidic protons capable of proton transfer or strong H bonding to the dye molecule. The dye and the developer are dissolved in a nonvolatile solvent, and the ternary composition is encapsulated. On heating, the organic solvent melts, resulting in color change. Some commonly used developers are bisphenol A, bisphenol B, 1,2,3-triazoles, thioureas, etc. Various compounds have been used as solvents, but the most common are aliphatic alcohols like stearyl alcohol. A puzzling feature of this system is that they are colored at low temperature and turn colorless at high temperature. Different reasons have been attributed to explain the same [10].

It has already been mentioned that the color development of the ternary system depends on the melting point of the solvent used. In order to ensure a homogeneous mixture throughout the color development stage, it is necessary to keep it in a closed system by microencapsulation. In a microcapsule, which is a small solid particle of 1–1000 $\mu$m size, there is a core containing the thermochromic system and a coating or shell of a polymeric material. Two processes are prevalent in the literature for microencapsulation of thermochromic dye systems. They are complex coacervation and interfacial/in situ polymerization.

In complex coacervation, two polyelectrolytes of opposite charges are used, such as gelatin and gum arabic [11]. At a pH of $<4.7$, the gelatin is cationic, and gum arabic is anionic. The core material is initially dispersed in the gelatin solution. To this dispersion, a solution of gum arabic is added, and the pH is adjusted to $\sim 4.0$. This causes a liquid complex coacervate (droplets) of gelatin-gum arabic and water to form, which surrounds the core to form embryo capsules. The system is then cooled to gel the shell. The shell is then cross-linked with glutaraldehyde and dried to form a free-flowing powder of microcapsules.

The shell formation in interfacial polymerization occurs due to polycondensation at the surface of the core material. Core material and one of the reactants, like multifunctional acid chloride or isocyanate, are mixed together to form a water-immiscible mixture. This mixture is dispersed in water with the aid of an emulsifier. The other reactant, e.g., multifunctional amine or alcohol, is added to the aqueous phase. Interfacial polymerization occurs at the surface of the core, forming the shell of the microcapsule. In situ polymerization is the technique adopted for forming shells of aminoplasts. The solid core material is first dispersed in water that contains urea, melamine, or water-soluble urea-formaldehyde condensate. An anionic polymer is added to enhance aminoplast shell formation. Formalin is then added, and the pH is adjusted to 2–4.5. On heating (40–60°C), shell formation occurs.

The microcapsules are used as conventional pigments and are coated on fiber or fabric with the aid of polymeric binders.

Shibahashi et al. have described the above technology in coating a variety of fibers [12]. The fibers have been converted into yarns, nonwoven fabrics, and knitted and woven fabrics of various constructions. All of these show thermochromic effect. By proper selection of the dye system, they have been able to obtain thermochromic effects at temperatures ranging from −30 to 100°C. For uniform color change, proper pigment particle size has been selected depending upon the density and the denier of the fiber. The proportion of dye, developer, and solvent are critical for optimum results. Besides, the add on has to be carefully chosen to keep a balance between clear color change and the texture of the textile material. In a typical formulation, a thermochromic composition consisting of 1 part by weight of crystal violet lactone, 3 parts of benzoyl-4-hydroxy benzoate, and 25 parts of stearyl alcohol, was encapsulated by coacervation in gelatin-gum arabic. The microcapsules were coated on the fibers by dipping in a polyurethane emulsion. The resulting fiber exhibited reversible thermochromism, turning blue above 53°C and becoming colorless below that temperature. By coating the system on a dyed fabric, they have been able to achieve change of color from one colored state to the other. Different binders have been used for coating. They include low melting point thermoplastics, natural and synthetic resins, and emulsions. Coating has been done mainly by dipping or spraying. The applications include apparel, toys, artificial flowers, etc. Thermochromic patterns have been obtained on fabric using thermochromic and uncoated fibers.

## 8.3 TEMPERATURE ADAPTABLE FABRICS

Textile materials are being increasingly used for architectural purposes. However, these lack the thermal insulation of the conventional building materials. The thermal insulation can be increased by a double-shelled construction or by adding a layer of foam to the textile material. A new way to improve the thermal insulation can be the application of phase change materials (PCM). When a substrate containing PCM is heated, by solar radiation, the increase in temperature of the substrate is interrupted at the melting point of the phase change material, due to absorption as latent heat. The temperature will rise only when all the solid has melted. Conversely, during the cooling process at low ambient, the drop in temperature is interrupted at the solidification temperature. The heat flux through a material containing PCM is thus delayed in both heating as well as cooling, during the process of phase change. This thermal insulation effect is dependent on temperature and time; and being temporary in nature, it can be termed dynamic thermal insulation.

Vigo and Frost [13,14] have incorporated polyethylene glycol of different molecular weights as PCM in hollow fibers resulting in a 2–2.5 times increase in heat content compared to the untreated material. Similar results were obtained by treating textile materials with aqueous solution of the PCM by pad dry method. The main drawback of the process is that the PCMs are water soluble.

Considerable improvement in technique has been done by Pause [15], who has used hydrophobic higher hydrocarbons like dodecane, octadecane, etc., as PCMs. These compounds were encapsulated to form microcapsules of 1–60 $\mu$m size. The microencapsulated PCM was applied by a thin layer of lacquer on PVC-coated polyester with foam backing. In order to meet the requirements of widely varying ambient of winter and summer months, two PCMs having different transition temperatures were used. A procedure was devised to measure the dynamic thermal insulation properties. A comparative study of coated fabric containing 40 g/m$^2$ micro-PCM showed a fivefold increase in thermal insulation. The technology has great potential and further development work is in progress.

## 8.4 CAMOUFLAGE NETS

Camouflage nets are meant to conceal military equipments and objects from detection and attack by an enemy. It has a great effect also on the morale of the fighting forces. Historically, camouflage nets were first used during World War I. The earlier nets were made of hemp/cotton twine, garnished with jute strip scrims, and dyed/coated with green and brown colors. These nets blended in with the surroundings and prevented detection by naked eye or by binoculars. These nets had serious limitations, such as poor camouflage properties, premature fading of colors, susceptibility to fungus growth, short life, and high water absorption, resulting in a great increase in weight of the net when wet.

With the rapid developments of sophisticated surveillance systems such as active and passive infrared sensors, infrared line scanners (IRLS), forward looking airborne radar (FLAR), side looking airborne radar (SLAR), millimeter wave radar, etc., it became imperative to develop camouflage nets that would protect the objects from detection by various sensors. The requirements of camouflage net can be summarized as follows:

- small volume and light weight
- strong and durable
- waterproof and fire resistant
- colors and patterns similar to the surroundings
- easy to deploy, transport, and handle
- conceals objects against detection by sensors

To meet these requirements, modern camouflage nets are wholly made of synthetic textiles. The nets available offer different levels of protection, viz, against visual and near infrared; visual, near infrared and microwave; visual, near infrared, thermal infrared and microwave; and ultraviolet for snow terrains.

### 8.4.1 VISUAL AND NEAR IR NETS

These nets camouflage the objects in the visual (400–700 nm) and near IR (700–1200 nm): regions of the electromagnetic spectrum. That is, they offer protection against visual detection and against NIR sensors, such as night vision devices and image intensifiers. In order to blend the objects with the surroundings, the reflectance of the nets in the visible and near IR regions (400–1200 nm) should match that of the surroundings. To achieve these characteristics in the net, it is necessary to know the reflectance pattern of the objects constituting the surroundings in this spectral region. A typical spectrum of green vegetation containing chlorophyll is given in Figure 8.2, showing an IR reflectance value of about 50%. From such spectra, the IR reflectance of other inanimate objects of the surrounding area are obtained (see Table 8.4) [16,17].

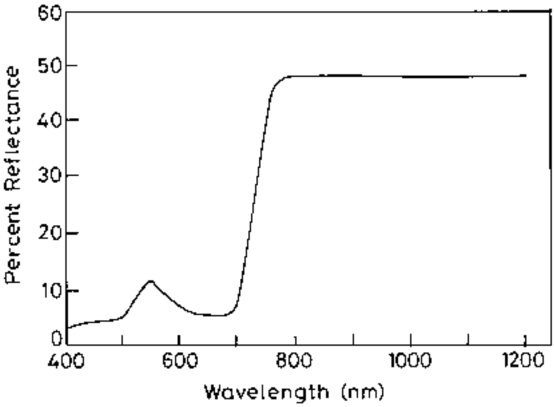

**Figure 8.2** Spectrum of green vegetation in visual and near IR.

TABLE 8.4. IR Reflectance Values of Some Common Objects.

| Constituents | Reflectance % |
|---|---|
| 1. Green vegetation | 50–70 |
| 2. Concrete | 40–50 |
| 3. Damp soil | 10–15 |
| 4. Dry soil | 15–20 |
| 5. Sand | 30–40 |
| 6. Building bricks | 30–40 |
| 7. Galvanized iron | 15–20 |

Two types of terrains are generally considered for camouflage, green vegetation and desert region. The color and IR reflectance of the net should match those of the terrain. Different nets are available for different terrains. A single net with reversible color pattern is also available.

The camouflage net consists essentially of two components, a netting forming the base and a garnishing material, usually coated fabric, that is fixed to the netting with clips. The netting is a square mesh of nylon twine, mesh size varying from 50–80 mm with soft vinyl coating or a flame retardant treatment. The garnishing material is usually PVC-coated nylon fabric incised in a suitable pattern. A lightweight fabric is taken as the base fabric ($\sim$70 g/m$^2$) that enhances the strength of the garnishing material. Unreinforced PVC films are also used for garnishing. The color scheme of the garnishing material depends on the terrain of deployment [18]. The colors for green belt are olive green, deep brunswick green, and dark brown. For the desert region, the colors are light stone, dark stone, and dark brown.

For effective camouflage in visual and near IR regions, the garnishing material should not only be of the desired color but should also have IR reflectance similar to that of the surroundings. For this purpose, pigment composition for PVC is first selected to obtain a visible match of the color. The level of IR reflectance is adjusted to the required value by introducing in the formulation normally a small percentage of high reflecting (e.g., $TiO_2$) or absorbing (e.g., carbon black) pigments. The nets are available in unit sizes of 1–1.7 m, which can be attached together to form a net of required size and shape. The incision in the garnishing replicates the shadows that occur in nature and breaks up the outline of an essentially rectangular or tubular nature of a vehicle or weapon system. The weight of the nets varies from 200–350 g/m$^2$.

## 8.4.2 RADAR CAMOUFLAGE NET

The most important component of a radar scattering net is the base fabric of the garnishing material. It consists of a specially designed nylon fabric in which is incorporated metallized yarns or aluminized polyester threads at regular intervals, both in warp and weft directions. The metallized threads form a regularly spaced grid structure in the fabric. The fabric is then coated with PVC compound containing pigments to meet the visual and near IR reflectance requirements. The coated fabric is incised in a definite pattern. By properly designing the grid structure of the metallized thread and with proper incision of the garnishing material, it is possible to scatter the incident microwave radiation from the radar, in a manner similar to that of the surroundings, leading to concealment of the object from radar. Nets made by Barracuda of Sweden have an attenuation of 10 dB against 3 cm radar (X band). It is claimed that the echo obtained from the object plus the net corresponds approximately to that of the surroundings [19].

### 8.4.3 SNOW CAMOUFLAGE

Snow has high reflectivity in UV region $\sim$90%. A standard white shade, on the other hand, has a poor UV reflectance, $\sim$10%. Thus, a military object when covered by standard white shade fabric in snow terrains, shows up as a black patch in a white background when viewed by reconnaisance devices using a UV filter at 350 nm. Camouflage nets for snow regions have a garnishing material of white PVC-coated nylon fabric having a UV reflectance of 75% minimum at 350 nm providing camouflage in both visual and UV regions.

## 8.5 METAL AND CONDUCTING POLYMER-COATED FABRICS

The incorporation of metal into textiles dates back to the Roman era, when they were mainly used for decorative purposes. The tinsel yarns used to add glitter to fabrics were made by flattening thin wire or sheets of noble metal like gold or silver. By the 1930s, aluminium foil strips coated on both sides by cellulose acetate-butyrate, to prevent them from tarnishing, were used. The yarn could be colored by anodizing. All of these yarns had poor compatibility with the more flexible and extensible textile yarns [20]. After the development of vapor-deposited aluminized polyester in the 1960s, 1 mm wide strips of these films were used as yarns, with much improved flexibility.

With the advancement of technology, metal/conductive textiles found extensive functional applications. These materials have high electrical conductivity and radar reflecting property, yet are lightweight and flexible. Various methods have been developed to coat fibers and textile materials by metals, and these are as follows [21]:

- coating metal powder with binders
- vacuum deposition

- sputter coating
- electroless coating

### 8.5.1 METHODS OF METAL COATING

*a.* Metal coating with a binder: the process is similar to conventional polymer coating. High leafing aluminium pastes (65–70%) are incorporated into a polymeric carrier, like synthetic rubber, PVC, polyurethanes, silicones, acrylic emulsions, etc., and spread coated on the fabric. The coating method may be conventional knife or roller coating. The adhesion, flex, and chemical resistance of the coated fabric depend on the type of polymer used, but they are not highly reflective.

*b.* Vacuum deposition: in this process, the substrate to be coated is placed in a chamber over a set of crucibles containing the metal to be coated in the form of a powder/wire. The chamber containing the whole assembly is evacuated to 0.5–1 torr. The crucible is heated by resistance heating to melt the metal. The temperature of heating is so adjusted that the vapor pressure of the metal exceeds that of the chamber pressure, so that substantial evaporation of the metal takes place. The temperature required for aluminium is about 1200°C. The roll of web to be coated is passed over a cooled drum placed over the crucibles. The metal atoms coming out of the molten metal hit the surface of the web to be coated and condense in the form of solid metal as it passes over the crucible. The production speed is quite high, ranging from 150–500 m/min. The items to be coated should be pretreated for proper adhesion of the metal. Continuous metal film coatings can be formed on just about any surface, film, fiber, or fabric with thicknesses ranging from micron to millimeter. Several metals can be vacuum evaporated, most common being aluminium, copper, silver, and gold. Difficulty arises in the case of metals, which sublime rather than melt and boil [21,22].

*c.* Sputter coating: the equipment consists of a vacuum chamber containing an inert gas, usually argon, at $10^{-3}$ to $10^{-1}$ torr (Figure 8.3). The chamber is equipped with a cathode (target), which is the source of the coating material, and an anode, which acts as a substrate holder. Application of an electrical potential of the order of 1000 Vdc, between the two electrodes, produces a glow discharge. A flow of current occurs due to movement of electrons from cathode to anode. The electrons ionize the argon gas. The argon ions are accelerated toward the cathode at a high speed due to high electric potential. The bombardment of the energetic ion on the target results in a transfer of momentum. If the kinetic energy of the striking ion is higher than the binding energy of the surface atoms of the material of the target, atoms are dislodged or sputtered from its surface by a cascade of collisions. Typically, the threshold kinetic energy of the ions should be between 10–30 ev for

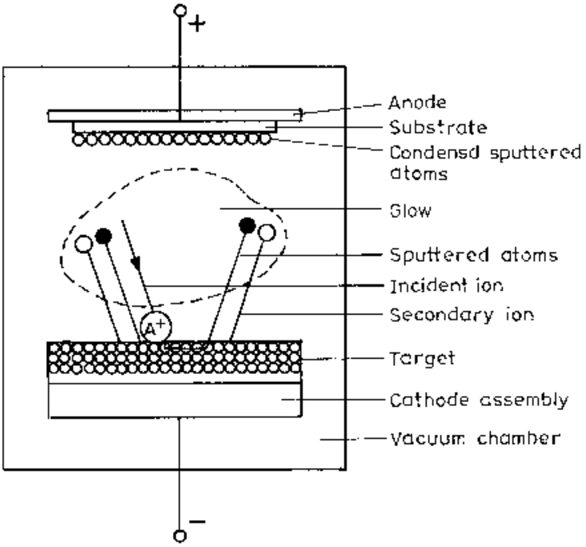

**Figure 8.3** Sputtered coating process.

sputtering from the surface. Some of the ions striking the target surface generate secondary electrons. These secondary electrons produce additional ions, and the discharge is sustained. Considerable heat is generated during the sputtering process, and it is necessary to cool the target. The sputtered atoms and ions condense on the substrate to form a thin film of coating [23,24]. The relative rates of deposition depend on sputter yield, which is the number of atoms ejected per incident ion. The sputtering yield varies with the target material and increases with the energy of the incident ion. The method is applicable to a wide range of materials and gives more uniform coating with better adhesion than simple vapor deposition. The process is, however, more expensive, and the rate of deposition is lower (~30 m/min).

*d.* Electroless plating: it is a process to deposit metal film on a surface, without the use of electrical energy. Unlike electroplating where externally supplied electrons act as reducing agent, in electroless plating, metallic coatings are formed as a result of chemical reaction between a reducing agent and metal ions present in solution. In order to localize the metal deposition on a particular surface, rather than in the bulk of the solution, it is necessary that the surface should act as a catalyst. The activation energy of the catalytic route is lower than the homogeneous reaction in solution. If the deposited metal acts as a catalyst, autocatalysis occurs, and a smooth deposition is obtained [25,26]. Such an autocatalytic process is the basis of electroless coatings. Compared to electroplating, electroless coating has the following advantages:

(1) Nonconducting materials can be metallized.

(2) The coating is uniform.

(3) The process is simple and does not require electrical energy.

Electroless coating is, however, more expensive.

For successful deposition of coatings, only autocatalytic reduction reactions can be used. As such, the number of metals that can be coated are not many. Some of the common reducing agents are sodium hypophosphite, formaldehyde, hydrazine, and organoboron compounds. Each combination of metal and reducing agent requires a specfic pH range and bath formulation. The coating thickness varies between 0.01 $\mu$m to 1 mm.

A typical plating solution consists of

*a.* Metal salt

*b.* Reducing agent

*c.* Complexing agents, required in alkaline pH and also to enhance the autocatalytic process

*d.* Buffers

*e.* Stabilizers, which retard the reaction in the bulk and promote autocatalytic process

Some important metal coatings are discussed below.

*a.* *Copper:* the most suitable reducing agent is formaldehyde. The autocatalytic reaction proceeds in alkaline pH (11–14). The commonly used complexing agents are EDTA, tartarate, etc. The overall reaction is given by

$$Cu^{+2} + 2HCHO + 4OH^{-} \rightarrow Cu + 2HCOO^{-} + H_2 + 2H_2O$$

*b.* *Nickel:* sodium hypophosphite is the most popular reducing agent for nickel. The autocatalytic reaction occurs in both acidic and alkaline pH. Sodium citrate is used as buffer and complexing agent. The reaction is given as

$$Ni^{+2} + 2H_2PO_2^{-} + 2H_2O \rightarrow Ni + 2H_2PO_3^{-} + H_2 + 2H^{+}$$

The coating obtained by sodium phosphite also contains phosphorus (2–15%).

*c.* *Silver:* the plating solution consists of ammoniacal silver nitrate with formaldehyde, hydrazine, and glucose as reducing agents. Because the autocatalytic activity of silver is low, thick deposits cannot be obtained.

Nonconducting materials like polymers are given an etching treatment by chromic acid, followed by a catalytic treatment using stannous chloride or palladium chloride solution. Electroless plating of textiles is being adopted for different functional applications. The details of which are mostly covered by patents.

## 8.5.2 USES OF METAL-COATED FABRICS

Metallized fabrics and fibers find diverse applications, many of them in high-tech areas. Some of the important uses are described below.

### 8.5.2.1 Protective Clothing

The heat reflecting property of the metallized fabrics is used for protection against intense radiant heat for short duration [20,27,28]. Such suits are required by firemen during firefighting and workers in the steel industry, for protection against blast furnace radiaton and molten metal splash. The development of these suits has been stimulated by the widespread withdrawal of asbestos as a heat-resistant material. Three types of suits are in use by firemen that offer different levels of protection given by the thermal protection index (TPI). TPI radiation and flames are defined as the time in seconds for the temperature of the back surface of the clothing assembly to rise by 25°C above the ambient when exposed to a standard radiant heat source of 20 $kW/M^2$ at a distance of 200 mm or exposed to a standard heat source of burning hexane (BS 3791). All of these suits contain a heat-reflective fabric, which consists of a polyester film vapor deposited by aluminium to a thickness of about 200 Å on both sides and is laminated to glass fabric by a high temperature adhesive. The smooth surface of the polyester provides a high level of reflectivity.

*a.* Approach suit: this suit is meant for close approach to fires and protection against radiant heat only. It is made of different layers, the outermost being the heat-reflective fabric, followed by a neoprene-coated fabric as a moisture barrier, and preferably an inner layer of flame retardant cotton fabric, in contact with the body. It has a TPI of 50 against radiation (BS 3791).

*b.* Proximity suit: these suits are for operating in proximity to flame and offer protection from radiant heat and occasional flame lick. The suit consists of at least three layers: the outer shell made of heat-reflective fabric, a moisture barrier, and a thermal barrier (NFPA 1976). The insulation layer may contain Kevlar® or carbon fiber fleece. The TPI is 80 for radiation and 18 for flame.

*c.* Entry suit: the suit permits firemen to enter the flame for a short period for rescue operation. The suit contains several layers of heat-reflective fabric and insulating layers, but the outermost layer should be noncombustible, like asbestos or special glass fabric with conductive coating. The TPI is the highest for these suits—300 for radiation and 100 for flames.

Kiln entry suits for workers also contain an aluminized polyester heat-reflective layer.

### 8.5.2.2 Radar Responsive Fabrics

Metallized fabrics are capable of reflecting electromagnetic radiation and can act as a radar target by giving strong echo. They have advantages over metals including being lightweight and easier to fabricate into different objects [29]. One of the main applications of these fabrics is for making lifesaving devices for locating persons marooned in high seas. These include caps for lost fishermen, life jackets for aircraft crew forced to drop into the sea during an emergency, and foldable radar fabric reflectors for life rafts. Besides, movements of meteorological balloons are tracked by providing targets of metallized fabrics on them. In defense application, a target banner is towed behind an aircraft at a distance for practicing surface-to-air firing by soldiers after locating the same on a radar. The fabric for the banner is made of monofilament yarn (polyethylene, nylon, viscose) containing metallized threads of duralumin or silver, in both warp and weft directions, in plain-weave construction. Target parachutes and target sleeves are also used for similar firing practice.

### 8.5.2.3 Static Electricity Control

Rubbing action between two nonconducting materials tends to generate a static electrical charge. Some typical examples are walking on carpet, flow of hydrocarbon gas through plastic pipe, and reciprocal motion between textiles. The charge buildup may suddenly release in the form of a spark. This may cause fire or explosion in contact with flammable substances. Static electricity may also cause damage to electronic circuitry. The conductivity of common textile fibers is of the order of $10^{-13}$ $(\text{ohm} \cdot \text{cm})^{-1}$. Increasing the conductivity to $10^{-3}$ to $10^{-10}$ $(\text{ohm} \cdot \text{cm})^{-1}$ range is usually adequate for dissipation of static charge [30]. Some examples of antistatic fabrics are staff apparel in electronic industry, filter panels, conveyor belt reinforcement, antistatic flooring, etc. A common method to reduce static charge buildup is to impart a hygroscopic finish to the material by phosphoric acid ester, quaternary ammonium compounds, etc. These compounds absorb moisture from the atmosphere, increasing the conductivity to $\sim 10^{-10}$ $(\text{ohm} \cdot \text{cm})^{-1}$ for static control. The drawbacks of these compounds are that their effectiveness depends on the humidity of the environment and that they are removed by washing [20,30]. Incorporation of conducting fiber is a sure way of dissipating static charge in textile. These fibers are carbon fibers, metal fibers, and metallized fibers. Carbon fibers impart black color to the textile, while metal fibers are difficult to mix with other fibers due to their brittleness and high density. Metallized fibers obtained by vacuum deposition or electroless coating have the advantage of being processed like any other textile fiber. Development of copper-, nickel- and silver-coated fibers by chemical method has been reported for antistatic application [30–32].

#### 8.5.2.4 Electromagnetic Interference Shielding

Any electrical or electronic device, including household appliances, generates electromagnetic radiation causing interference. These, in turn, can be disturbed by other devices. Various other sources of interference are cosmic rays, lightning, and high voltage power cables. The trend toward faster, more powerful electronic equipment and denser circuitry has increased the possibility of electromagnetic and radio frequency interference (EMI and RFI). This development presents a challenge to scientists to control EMI emission as well as to shield sensitive electronics from EMI to meet strict international regulations. Metallized fabrics are emerging as a material of choice for EMI/RFI shielding of sensitive equipment, particularly in defense and in aerospace. The conducting fabric can be tailored to ready-to-use adhesive tapes, curtains, bags, etc.

In order to understand the shielding process, let us consider an electromagnetic wave impinging on a shielding screen. The incident wave will undergo reflection from the surface, absorption by the material of the screen, and secondary reflection. The attenuated wave is transmitted from the other side of the screen. The shielding efficiency is expressed in decibel (dB) and is given by:

$$\mathrm{SE}_{dB} = 20\log_{10} E_I/E_T \quad \text{(for electrical field)}$$

$$\mathrm{SE}_{dB} = 20\log_{10} H_I/H_T \quad \text{(for magnetic field)}$$

where $E_I$ and $H_I$ are the incident electrical and magnetic fields, and $E_T$ and $\mathrm{H}_T$ are the transmitted fields. The shielding efficiency increases with the conductivity of the fabric and thickness of the coating.

Various metal-coated fibers and fabrics have been reported in the literature for EMI shielding. Texmet brand of fibers are obtained by deposition of copper and nickel on acrylic fiber by a chemical process. A coating thickness of 0.3 $\mu$m gives a conductivity of $10^3$ $(\mathrm{ohm}\cdot\mathrm{cm})^{-1}$. The fiber is available in the form of crimped staple fiber or as continuous tows. Nonwoven fabrics of different conductivities have been made by incorporating Texmet fiber into other textile fibers, like polyester, polypropylene, and acrylic. Nonwoven with 70% Texmet loading showed very good microwave reflection and a transmission loss of over 65 dB in the 8–12 GHz range [30]. Temmerman [31] has described an electroless coating process known as Flectron (a brand name of Monsanto Chemical Co.). Metal coating of copper, nickel, silver, etc., singly or a combination of one metal with an overcoat of a second metal has been done by this process on a variety of substrates, including woven, knitted, nonwoven fabrics, chopped strands, and films. The metal content of these fabrics ranges from 14–24 g/m$^2$, with surface resistivity varying from 0.04–(0.43 ohms/sq (see AATCC test method 76-1995). A coating of 15 g/m$^2$ metal, Cu, Cu/Ni, or Sn/Cu on nylon nonwoven gave a shielding between 56–90 dB in the frequency range of 100 to 10,000 MHz. It was estimated that these metallized fabrics provide 95–97% of the shielding than would be provided by an equivalent mass of metal in foil form. The metal layers are well adhered on the substrate. Silver-coated nylon fiber and nylon fabric have also been developed by Statex system of coating for different applications [32], including EMI shielding. Shielding of over 40 dB has been obtained in 90 GHz to 500 MHz range using silver-coated nylon fabric.

Apart from the above specialized applications of metal-coated fibers/fabrics, they are also used for several other purposes. The passage of an electric current through metal-coated panels of fabric results in resistive heating. This property can be used for making heated garments, gloves, blankets, and as an IR tank decoy [33]. Some other uses are ironing board covers and pleated window shades for thermal protection. A comprehensive list of applications of these fabrics has been given by Smith [21].

### 8.5.3 CONDUCTING POLYMER COATINGS

Several people have been working on the development of conducting polymer-coated textiles. Major problems of these coatings are their poor environmental stability and difficulty in processing them from solution or melt. As such, the technology is still in the developmental stage. The polymers that have been tried are polypyrrole and polyaniline. Coating of polypyrrole on textiles has been done by Jolly et al. [34] in a one-step process, in an aqueous solution containing the monomer, $FeCl_3$ oxidant and napthalene sulphonic acid dopant, at a reaction temperature of 5–10°C. Polymerization occurs at the surface of the textile, and each fiber is coated with a homogeneous polypyrrole layer. The coated fabric has a surface resistivity of about 10 ohms/sq and has been tried as heating panels for buildings. Effect of aging on the conductivity has also been studied at different temperatures. Jin and Gong [35] have deposited polyaniline on polyester fiber and nylon fabric by aniline diffusion and oxidative polymerization, using HCl as a dopant. The process consists of immersing the textile in aniline and removing the absorbed aniline from the surface by treatment with hydrochloric acid. The specimens were then treated with aqueous aniline hydrochloride solution, followed by oxidation with ammonium persulphate, and washed. Aniline diffusion and use of HCl as dopant enhanced the conductivity and adhesion of the coating. Polyaniline and polypyrrole coatings have also been studied by Trivedi and Dhawan [36] and Gregory and coworkers [37].

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## CHAPTER 9

# Test Methods

THERE are a number of tests used to evaluate coated textiles. The basic principles and relevance of the tests typical to coated fabrics are discussed in this chapter. Tests that are common to uncoated textiles, such as roll characteristic (length, width, and mass), breaking strength, tear resistance, and bursting strength, have not been included. ASTM-D 751-79 prescribes that all tests are to be carried out after a lapse of at least 16 h between curing and testing. Specimens are cut in such a way that no specimen is nearer than one-tenth of the width of the fabrics. The conditioning of the specimens is done at specified conditions of temperature and humidity depending on the standard used, i.e., ASTM, BS, Indian Standard, DIN, etc.

### 9.1 COATING MASS PER UNIT AREA (BS 3424, IS 7016 PART 1)

Three test specimens of 2500 $mm^2$ areas in circular, rectangular, or square shapes, are cut, conditioned, and weighed. The result is expressed in $g/m^2$. The coating of these specimens is then removed by selecting a proper stripping solution for the particular nature of coating. The bulk of the coating is removed mechanically by wetting the specimens with stripping solvent. The specimens are then refluxed with the solvent, washed with acetone, dried, and weighed. The process is repeated until the difference is $<1\%$ between successive refluxing and washing. The stripping solvent for PVC is tetrahydrofuran or methyl ethyl ketone. For natural rubber on cotton, nitrobenzene/xylene is used. PU-coated fabrics are stripped by 2 N alcoholic KOH. The weight of the base fabric thus obtained is also expressed in $g/m^2$. The coating mass in $g/m^2$ is obtained by subtracting the weight of the base fabric from that of the coated fabric.

In a rubberized fabric, the rubber hydrocarbon (polymer) content can be determined either by indirect method or by direct method. In the indirect method, the nonrubber ingredients are estimated from the contents of acetone, chloroform, alcoholic potash extracts, and determination of fillers and sulfur contents.

The rubber content is obtained by difference. This method is applicable for all olefinic rubbers. Direct method covers the determination of specific rubber polymer in the product based on the estimation of an element or a functional group. Thus, natural rubber content can be estimated from the acetic acid generated on its oxidation by chromic acid. In a similar manner, estimation of nitrogen or chlorine by standard techniques permits calculation of nitrile rubber or neoprene content, respectively (IS 5915 and 6110).

## 9.2 DEGREE OF FUSION/CURING OF COATING (BS 3424, ASTM D 4005-81)

PVC is generally coated as a dispersion in a solvent by the spread-coating process. After coating, the layer is fused to form a uniform film. During fusion, phase inversion occurs. Proper fusion determines the durability of the coating. Three test specimens of 40 × 25 mm are cut from the roll of the fabric. The specimens are immersed for 15 min in acetone at 20°C (BS) or 30 min at 23°C (ASTM), and the coating is examined. If there is no cracking or disintegration of the coating, disregarding surface effect or removal of lacquer, the sample is considered to have passed.

For rubberized fabrics, the specimens are immersed in xylol for 2 h at 27°C, and the coating is examined. The sample is considered to have cured if there is no tackiness in the coating or no detachment from the base fabric (IS 9491).

## 9.3 BLOCKING (BS 3424, IS 7016 PART 9)

This test is to check the tackiness of the coating at elevated temperature, so that the coating is not damaged when stored in rolls. In the BS method, two specimens of 150 × 75 mm are cut from the roll, placed face to face covering each other completely, placed in an oven at 60°C with a 1.5 kg weight piece placed over it, covering half the area of the specimen pair, and kept for 15 min. The specimens are then taken out, and a 100 g weight is hooked on the free end of the lower strip. No blocking is reported if the upper strip can be separated from the bottom strip at 25 mm/s rate of pull without lifting the 100 g weight piece, and there is no visible damage to the surface of the specimen.

In the IS method (based on ISO/DIS 5978-86), six specimens each of 150 × 150 mm are cut. The specimens are piled in three pairs, back to back, back to face, and face to face. The three pairs are placed in such a way that 100 $mm^2$ pile is formed, leaving the rest of the area free. The pile is placed between two glass plates in an oven at 70°C. A 5 kg weight piece is placed over the pile assembly. The specimens are taken out after 3 h, cooled at ambient for 3 h, and examined. No blocking is reported if the specimens can be separated without any sign of adhesion. This method examines blocking between the coated and uncoated surfaces.

## 9.4 COATING ADHESION (BS 3424, ASTM D-751, IS 7016 PART 5)

This test is of importance because if the adhesion is inadequate, separation of the coating from the base fabric may occur. As per BS, test specimens of 75 × 200 mm with length perpendicular to the longitudinal axis are cut. If the coating is thick, i.e., where the strength of the coating is more than the adhesive bond between the coating and the fabric, the coating is manually stripped to about 50 mm, and the width of specimen is trimmed to 50 mm. The adhesion strength can be determined by either a dynamic method or a dead weight method. In the dynamic method, the separated plies of the specimens are clamped to the jaws of an autographic strength testing machine with constant rate of traverse. Coating is separated for about 100 mm by setting the traverse jaw in motion. The adhesion strength is obtained from the load required to separate the coating layer.

The dead weight test apparatus consists of two grips, the top fixed to a rigid support and the bottom free, capable of accepting dead loads of 200 g units. The separated plies of the specimen are attached to the two grips, and dead weight is gradually placed on the lower jaw until separation occurs within a specified rate (5 mm in 5 min). This load is recorded. If the thickness of the coating is thin, two specimens are bonded face to face by an adhesive system leaving 50 mm free. For vinyl coating, the adhesive may be a solution of PVC resin in tetrahydrofuran, and for PU coating, suitable PU adhesive is taken. At the adhesion line of the two specimens, one layer of fabric and both layers of coating are cut and manually stripped to a specified distance. The adhesion strength is determined as above by fixing one layer of base cloth in the fixed jaw and the composite layer of two coatings and base cloth in the movable jaw.

ASTM and IS procedures are similar except that they specify only a dynamic tensile testing machine for adhesion and that the shape of the peeled layer of coating of the specimen is in the form of a tapered tongue (Figure 9.1).

## 9.5 ACCELERATED AGING (BS 3424, IS 7016 PART 8 BASED ON ISO/R 1419-1970)

Two methods are prescribed for accelerated aging: oven method and oxygen pressure method. In oven aging, specimens are heated in an air oven at 70°C or 100°C, as required, for 168 h. After the exposure, the nature of the coating is observed for any sign of softening, stiffening, brittleness, or sticking. Determination of a physical property before and after aging permits the calculation

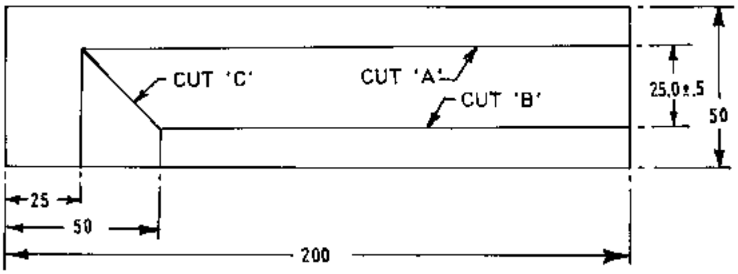

**Figure 9.1** Dimensions and cutting line of test piece (IS 7016 Part V). Cut A extends from one end of the test piece to within 25 mm of the other end. Cut B extends to within 50 mm of that end. Cut C is a diagonal cut joining the ends of cut A and B (all dimensions in mm). (Adapted with permission from Bureau of Indian Standards.)

of percentage loss of the physical property on aging. In the oxygen pressure aging test, the specimens are subjected to elevated pressure and temperature by hanging them vertically in a pressure chamber of stainless steel at an oxygen pressure of 2000 kN/m$^2$ and 70°C for 24 h.

For vinyl-coated fabrics, estimation of loss of plasticizer is of great importance as it gives an idea of the durability of coating on weathering of these fabrics. ASTM-D1203 describes estimation of loss of volatiles from coated fabrics under defined conditions of time and temperature using active carbon as the immersion medium. In the direct contact method (A), three specimens are placed in a covered container with alternate layers of active carbon of specified particle size. The container is heated in an oven at 70°C for 24 h. The weight loss of the specimens is measured. Method B, known as the wire cage method, is similar to method A, except that the specimens are placed in the annular space of a cylindrical metal cage made of bronze gauze and are not in direct contact with active carbon. The wire cage method is similar to the BS method. In the IS method (IS 1259), the loss of mass as volatiles is estimated by exposing test specimens at 100°C for 24 h in an air oven.

For elastomer-coated fabrics, ASTM D3041 describes an ozone cracking test. The specimens are under strain by placing them around a mandrel and are exposed in a ozone test chamber containing an atmosphere of ozone and air (50 mPa partial pressure of ozone), and at a temperature of 40°C. The specimens are examined for cracks by magnifying glass after exposure for a specified duration of time.

A stringent accelerated aging test has been given for inflatable restraint (air bag for automobiles) fabric in ASTM D 5427-95. The fabric specimens are evaluated for selected physical properties after cyclic, heat, humidity, and or ozone aging. In cyclic aging, the specimens are aged in a specified cycle of temperature and humidity conditions. Typical aging cycle conditions are (a) −40°C, ambient RH for 3 h; (b) 22°C, 70% RH for 2 h; and (c) 107°C, ambient RH, for 3 h. The conditions for heat aging, humidity aging, and ozone aging

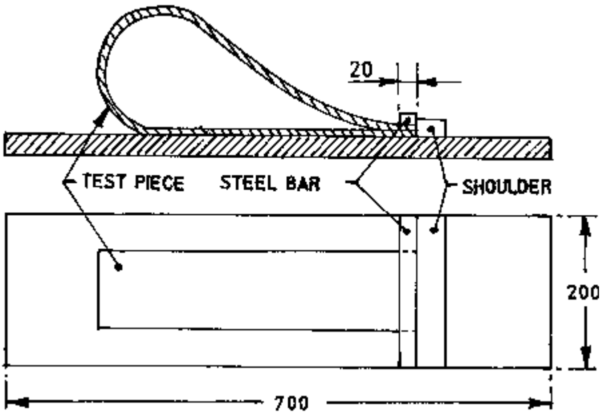

**Figure 9.2** Apparatus for flexibility determination (IS 7016 Part 11) (all dimensions in mm). (Adapted with permission from Bureau of Indian Standards.)

are 105°C for 400 h; 80°C, 95% RH for 336 h; and 40°C, 65% RH, 100 pphm ozone concentration for 168 h, respectively.

## 9.6 FLEXIBILITY—FLAT LOOP METHOD (IS 7016 PART 11 BASED ON ISO 5979-1982)

This simple test measures the flexibility of rubber- or plastic-coated fabric. Rectangular strips of 600 mm × 100 mm are cut. A loop is formed from the strip and placed on a horizontal plane by superposing the two ends that are held in place under a steel bar (see Figure 9.2). The height of the loop is measured, which gives an idea of the flexibility of the fabric. The lower the loop height, the greater the flexibility, and vice versa.

## 9.7 DAMAGE DUE TO FLEXING (BS3424, IS 7016 PART 4, ASTM D 2097)

Accelerated flexing of coated fabrics gives useful information of the durability of the coating in actual use. One of the common methods described in the BS/IS standards for flex testing is the De Mattia method. The apparatus consists of pairs of flat grips. The grips of each pair are positioned vertically one over the other, and one grip is capable of reciprocating motion in a vertical plane. The traverse distance of the grips in open and closed positions is 57 mm. The rate of reciprocating motion of the grips is specified (300 cycles/min). Test specimens of 45 × 125 mm are cut with length in longitudinal and cross directions. Each test specimen is folded with coating outwards along lines 15 mm from each of the longer sides and to a width of 15 mm. The specimens are then clamped between the grips of the equipment and flexing is carried out for specified cycles (∼100,000 cycles). The specimens after flexing are examined for number of cracks, their severity, and delamination.

ASTM D 2097 is meant for upholstery leather but has been adopted for vinyl upholstery fabric (ASTM D-3690). The testing is carried out in Newark-type flexing machine containing a pair of pistons. One piston of the pair is stationary, and the other is movable. The piston moves with a reciprocating motion in a horizontal plane at 500 rpm with a stroke of 32 mm. The closed position of the piston is adjusted to 15 times the thickness of the specimens. The sizes of test specimens are 76 × 114 mm and are clamped on the pair of pistons in a cylindrical shape. After a predetermined number of cycles, the fabric is visually examined for cracks.

## 9.8 ABRASION RESISTANCE (ASTM D-3389, BS 3424)

The abrasion resistance of a coated fabric is determined by abrading the coated surface of the fabric with an abrader. Measurement of mass loss after abrasion gives an idea about the abrasion resistance of the coating. In the ASTM method, a revolving double-headed platform (RPDH) abrader is used. Circular test specimens of 110 mm diameter are cut and placed with the coated side up on a specimen holder affixed on a rotating platform. The platform is rotated in a circular motion at 70 rpm. The abrasion is done by two abrasive wheels made of a specified material that are attached to the free end of a pair of pivoted arms. The abrasive wheels rest on the specimen in a manner that a vertical force is applied on the specimen by them. The force can be increased by the addition of weights. The abrasion occurs due to friction between the rotating specimen and the abrasive wheels. The loose abraded particles are removed from the specimen by vacuum cleaner. From the mass loss of the specimen for specified cycles of operation, the mass loss per revolution is estimated.

The BS specifies the Martindale abrasion tester for testing expanded PVC coating. The machine consists of a rectangular base plate on which are mounted four circular discs covered with specified silicon carbide paper. A top plate containing a four-specimen holder rests on the center of the abrading discs. Four circular test specimens are cut and placed on the specimen holder, with coated surface facing the abrading disc. A specified load is applied on the specimens by placing desired weights. The abrasion occurs due to the rotation of the plate holding the specimens, such that the specimen rubs against the abrading disc in a definite pattern. The pattern traced by the plate is similar to Lissajou's figures, i.e., it changes from a circle to gradually narrowing ellipses to a straight line followed by gradually widening ellipses to a circle. After a specified number of cycles, the exposure of the cellular layer of the coated fabric is noted.

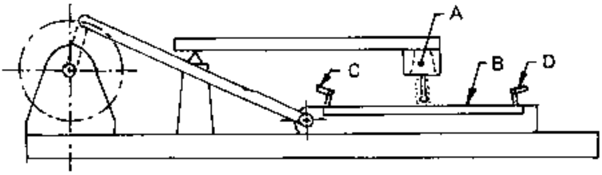

**Figure 9.3** Apparatus for measuring colorfastness to rubbing (IS 1259): (A) abrader member, (B) glass plate, and (C, D) grips. (Adapted with permission from Bureau of Indian Standards.)

## 9.9 TEST FOR COLORFASTNESS TO DRY AND WET RUBBING (BS 3424, IS 1259)

The test essentially consists of rubbing the coated fabric specimens with white fabric with a specified load and number of cycles and examining the stain imparted, if any, on the white fabric from the test specimen. The test is also known as colorfastness to crocking and is carried out in a crockmeter. Test specimens of 230 × 50 mm are cut from the roll and mounted with coated side up on a flat glass surface. A circular piece of bleached white fabric of 25 mm diameter is affixed to a circular brass abrading peg of 16 mm diameter. The abrading peg is fixed to a pivot by an arm. The peg is imparted a reciprocating motion in a straight line parallel to the surface of the test specimen, either manually or mechanically, with a stroke of 100 mm at a rate of 15 cycles/min and is loaded in a manner to exert 0.5 kgf on the test piece. In dry rubbing, the staining of the cotton fabric is examined after ten abrading cycles and compared with the gray scale. In wet rubbing, the cotton fabric is wetted by diluted soap-soda solution prior to rubbing. Apparatus specified in the IS standard is shown in Figure 9.3.

## 9.10 LOW TEMPERATURE BEND TEST (ASTM D 2136, IS 7016 PART 10, BASED ON ISO 4675-90)

Coated fabrics are used in many applications requiring low temperature flexing. This method is meant for evaluation of the ability of rubber- and plastic-coated fabrics to resist the effect of low temperature, when subjected to bending.

Three test pieces of 25 × 100 mm are cut from the rolls. Each specimen after conditioning is placed between a pair of glass plates, to prevent curling, and then placed into a low temperature cabinet maintained at the specified temperature. A bending jig for bending the sample after exposure is also placed in the cabinet. The bending jig consists of two rectangular aluminium blocks. The blocks are connected by a hinge and aligned in a straight line. The two blocks are mounted in a frame at an angle of 60° from the horizontal (Figure 9.4). To the top block is attached a 250 g weight. A release mechanism folds the hinge at 180° so that the upper plate with weight falls free for bending the specimen. After the

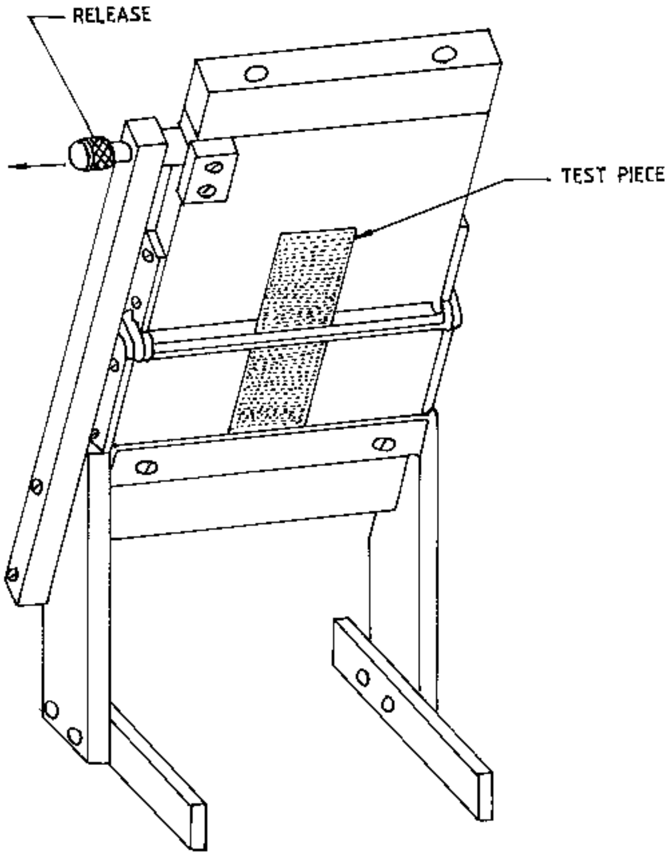

**Figure 9.4** Bending jig for low temperature bend test. (Adapted with permission from Bureau of Indian Standards.)

end of the exposure period (4 h), sample specimen is placed in the jig and bent within the cabinet itself by the release mechanism. The samples are then taken out, folded at 180°, and examined for cracks and their severity.

## 9.11 LOW TEMPERATURE IMPACT TEST (BS 3424, ASTM D-2137, IS 7016 PART 14)

This is another test to determine the applicability of rubber- and plastic-coated fabrics at low temperatures. By this method, the lowest temperature at which the fabrics do not exhibit cracks in the coating when subjected to specified impact conditions is measured. In the ASTM method, test specimens of 6.4 × 40 mm are die punched, conditioned, and one end is clamped in a specimen clamp designed to hold the specimen as a cantilever beam, such that

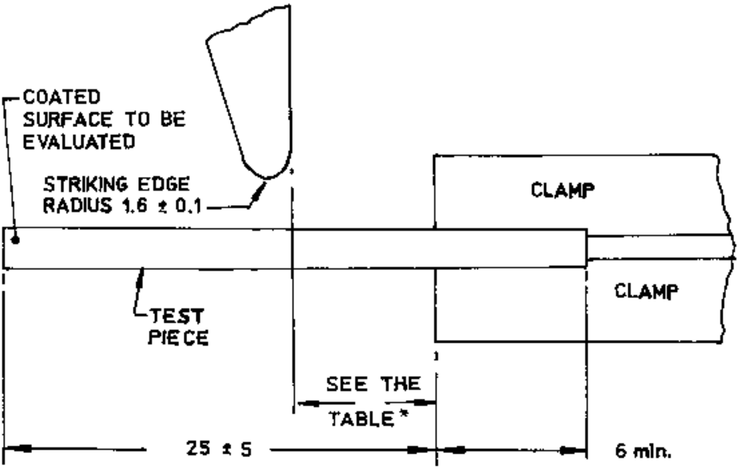

**Figure 9.5** Test piece holder and striker in low temperature impact test. *Refers to Table 1 of IS 7016 pt. 14 specifying clearance of striking arm and test piece clamps for test pieces of different thicknesses (all dimensions in mm). (Adapted with permission from Bureau of Indian Standards.)

the length extending from the clamp is 25 mm. A solenoid-activated striker is positioned on top of the specimen to impart an impact on it. The radius of the striking arm, the position of strike at the specimen from the clamp, the traverse distance of the striker, and the speed of traverse are specified. The test piece holder and striker specified in IS are shown in Figure 9.5. The cold crack temperature varies with the rate of folding, and as such, it is essential to fix the impact velocity at 2 m/s. The test assembly (specimen, clamp, and striker) is immersed in a low temperature bath of methanol, silicone, or other suitable heat transfer fluid, or in a refrigerated cold cabinet. After temperature equilibration, impact is applied on the specimen through the striker and cracks in the coating examined by taking out the specimen. The temperature of the bath is lowered by intervals at 10°C until the specimen fails. The temperature of the bath is then raised by 1°C intervals until the specimen passes. The temperature 1°C below this point is the cold crack temperature.

In the BS method, a folded test piece in the form of a loop is placed on an anvil and immersed in a low temperature bath by a holder. Impact is provided by a spring-actuated hammer of specified weight. The impact velocity is maintained at 2 m/s. Cold crack temperature is determined in a similar manner.

## 9.12 CONE TEST (IS 7941)

This is a test for the waterproofness of the fabric that is locally stressed. A circular/rectangular specimen of fabric is folded twice and then opened to obtain a cone with the coated side inward. At the tip of the cone, the material is folded so sharp that the coating is heavily stressed. The cone is then put in a wire cone and, in turn, placed into a glass funnel and filled with a specified quantity of water. There should not be any penetration of liquid, as well as no wetting of the outer surface of the specimen cone after 18 h.

## 9.13 RESISTANCE TO WATER PENETRATION (ASTM D-751, BS 3424, IS 7016 PART 7)

This test is of great relevance for coated fabrics because it evaluates the continuity of coating film and its resistance to water penetration, which is an important property of certain fabrics, particularly those used as rainwear, covers, and inflatables. ASTM describes two methods. Method A uses a Mullen-type hydrostatic tester, and in method B, pressure is applied by a rising column of water.

In a Mullen-type hydrostatic tester, a test specimen is clamped between two circular clamps having an aperture of 31.2 mm diameter. Hydraulic pressure is applied to the underside of the specimen by means of a piston forcing water into a pressure chamber. The pressure is measured by a Bourdon's gauge. During testing, steadily increasing pressure is applied on the specimen, and the pressure is noted when water first appears through the specimen. Alternately, a specified pressure is applied on the specimen for 5 min and appearance of water through the fabric is noted. A specimen is considered to have passed if there is no leakage of water at that pressure. Method A is not applicable for fabrics having water resistance less than 35 kPa pressure.

In method B, the test specimen is mounted on a ring with a conical bottom with the coated surface in contact with water. The specimen is clamped by placing a dome-shaped movable water chamber at the top. The water chamber has a water inlet and a vent. A water leveler consisting of a water inlet, a water outlet, and an overflow pipe is attached to the inlet of the chamber and is the means for setting the head of water. The overflow pipe regulates the level of water. During test, the head of water is increased by raising the water leveler by a motorized system, at the rate of 1 cm/s. The pressure at which the first drop appears through the underside of the specimen is noted. In an alternative procedure, the head of water is kept steady for a specified period, and leakage, if any, is noted. The low pressure method of BS, IS, and the hydrostatic pressure test of AATCC 127 are similar.

## 9.14 AIR PERMEABILITY (BS 3424)

The air permeability of coated fabric is low. This method is used primarily for porous discontinuous coating of breathable fabric. Air permeability is defined as the volume in milliliters of air that passes through the fabric per second, per

$cm^2$, at a pressure of 1 cm head of water. The apparatus described in the standard consists of a specimen holder, in which the specimen is clamped between two flanges having an orifice of 25 mm diameter (a test area of 5.07 $cm^2$). Air is sucked through the test specimen by means of a vacuum pump. The rate of flow is adjusted by a series valve and a bypass valve, setting the pressure drop of 1 cm water head, across the fabric which is indicated by a dial gauge. The rate of flow of air is measured by an appropriate rotameter when steady pressure drop of 1 cm head of water is achieved. The apparatus is based on the Shirley Institute, U.K., air permeability apparatus.

## 9.15 WATER VAPOR PERMEABILITY (ASTM E-96-80)

Water vapor permeability is an important parameter of breathable fabric, as it gives an idea about the comfort property of the fabric. The ASTM method is, however, a general method for all materials, like paper, plastic, wood, etc., and not specifically for textiles. Two methods are described, viz., the desiccant method and the water method. The details of the two methods are described below.

### 9.15.1 DESICCANT METHOD

For the test, a shallow test dish is taken. The weight and size of the dish should be such as that can be weighed in an analytical balance, having a mouth of at least 3000 $mm^2$ area. The dish should have a ledge around the mouth to fix the test specimen. A layer ($>12$ mm) of anhydrous calcium chloride of specified mesh size is filled in the dish within 6 mm of the specimen. The mouth of the test dish is covered with test specimen, and the edges are sealed by molten wax. The whole assembly is weighed and placed in an air circulated, temperature and humidity controlled test chamber. The temperature of the chamber can be maintained at a selected value, but a temperature of 32°C is recommended. The humidity of the chamber is maintained at 50% or 90% RH depending on the environment desired. The weight gain of the test assembly is measured periodically, and at least 10 data points are taken during the duration of the test. A plot of weight against elapsed time is drawn. The slope of the straight line plot gives $G/t$ (where $G$ is weight change in gms and $t$ is time in h). The water vapor transmission is given by $WVT$ (g/h/$m^2$) $= (G/t)A$ ($A$ is the area of the exposed specimen in $m^2$).

### 9.15.2 WATER METHOD

In this procedure, the test dish is filled with distilled water to a depth of 3–5 mm, with air gap of about 20 mm from the specimen. The procedure is the same as that for the desiccant method. The weight loss is measured periodically. If the barrier material is expected to be in contact with water in service, the dish is inverted during the test.

The BS 7209 method for estimation of water vapor permeability index % ($I$), for breathable fabric, is similar to the water method of ASTM. However, in this specification, the test specimens are tested along with a specified reference fabric, for water vapor permeability, and from the ratio of their water vapor permeability, $I$ is calculated. The reference fabric is made of monofilament high tenacity woven polyester yarn of 32 $\mu$m diameter having an open area of 12.5%. As per the procedure, test specimens/reference fabric are sealed over the open mouth of a test dish, with cover ring of specified dimensions, containing distilled water. The quantity of water is adjusted to maintain a still air of 10 ± 1 mm between the underside of the specimen and the surface of the water. A sample support placed on the mouth of the dish prevents sagging of the specimen and the resultant change in the depth of the still air layer. The whole test assembly is placed on a rotating turntable. The turntable with the test assemblies are, in turn, placed in an environmental chamber, maintained at 65% RH, and 20°C temperature. The turntable is rotated at a slow specified rate to avoid formation of a still air layer above the dish, care being taken that the depth of still air is not altered inside the dish due to rotation. The test assemblies are weighed after a period of ~1 h to permit equilibration of water vapor gradient in each assembly. Dishes are then placed back on the turntable in the chamber, and the test is continued for a period of ~16 h, after which the assemblies are reweighed. From the loss of mass of the assemblies between the two weighings, the index $I$ is calculated.

$$\text{Water vapor permeability in g/m}^2\text{/day} = 24M/At$$

where $M$ = loss of mass in g of assembly in time $t$ (h), and $A$ = area of the test fabric in $\text{m}^2$ exposed.

$$I = \{(wvp)_f/(wvp)_r\} \times 100$$

where $(wvp)_f$ and $(wvp)_r$ are the mean permeability of test specimens and that of reference fabric, respectively.

## 9.16 RESISTANCE TO PERMEATION BY HAZARDOUS LIQUID CHEMICALS (ASTM F 739-96)

This test determines the resistance to permeation of a hazardous liquid through protective clothing material under continuous contact. The apparatus consists of a glass cell with two compartments, with the test specimen placed in between. One compartment is filled with the hazardous liquid, while the other contains a collecting fluid to absorb the permeated material. The test specimen acts as a barrier between the challenge chemical and the collecting medium. The collecting fluid may be a liquid or a gas in which the hazardous liquid is freely soluble. The chemical permeating through the specimen dissolves in the collecting fluid and is analyzed continuously or discretely by a suitable analytical technique. Some common techniques are UV, IR, spectrophotometry, gas liquid chromatography, and colorimetry. The barrier property of the material of the specimen is evaluated by measuring the breakthrough time (BTT) as well as permeation rate. The BTT is the time elapsed in seconds between the initial contact of the chemical with the outside surface of the specimen and the time at which the chemical can be detected at the inside surface by the analytical tool.

## 9.17 RESISTANCE TO PENETRATION/PERMEATION OF CHEMICAL WARFARE AGENTS [1]

These tests are meant for evaluating protective clothing against chemical warfare agents (NBC clothing) that manifest their effect by absorption through skin (viz., vesicant and nerve gases as discussed in Chapter 8, section 8.1). Among the various chemical agents, sulfur mustard is known to be the most penetrating in nature, and any permeable or impermeable fabric found to be effective against it ought to give a better or the same degree of protection against other members of the category. There is a lot of variation in the test methods of various countries. Prints Maurits Lab. TNO, The Netherlands, have developed and standardized various test methods, keeping in view all possible modes of exposure. These methods find widest acceptance. Two methods most commonly used for evaluation are discussed below.

### 9.17.1 TESTING FOR PROTECTION OF PERMEABLE CLOTHING AGAINST MUSTARD GAS VAPOR

This test is meant for vapor challenge of permeable clothing. One and one-half cm$^2$ of a complete clothing assembly (NBC overgarment, combat cloth, and underwear) positioned in a glass cell is exposed to an airstream of 5 m/s perpendicular to the fabric. The air (5400 L/h) is contaminated with mustard gas vapor in a concentration of 20 mg/m$^3$. The whole system is at room temperature (20–22°C) and at a RH of 30–80%. Through the underside, air is sucked at a speed of about 0.3–0.5 cm/s depending on the resistance to air of the complete assembly. The amount of mustard gas penetrated is collected in a bubbler from this airstream. The solvent used in the bubbler to trap the mustard gas vapor is either methylisobutylcarbinol (1–2 ml), when the bubbler is exchanged automatically every hour, or diethylsuccinate (1 ml) when only one bubbler is used in 6 hrs. The amount of mustard gas collected in the solvent is determined by gas liquid chromatography with flame photometric detector. The sample is considered to have passed the test if the collected amount of mustard in 6 hrs is $<500$ mg/min/m$^3$.

### 9.17.2 TESTING FOR PROTECTION OF CLOTHING AGAINST LAID DOWN MUSTARD GAS DROPS

This test is for testing the effectiveness of both permeable and impermeable clothing against liquid challenge. A complete assembly combined with a polyethylene film (0. 015 mm) is positioned on a horizontally oriented glass cell. The specimen is fixed with a glass ring of 3–5 mm height and rubber springs. The exposed surface area of the sample is 1.5 cm$^2$. There is a flow of air parallel to the surface of the test specimen of 0. 5 m/s. A droplet of 1 $\mu$L mustard gas is placed onto the outer fabric corresponding with a contamination density of 8.3 g /m$^2$. A flow of air (L/h) underneath the polyethylene film transports the penetrated mustard gas vapor to a bubbler. The vapor is trapped in a solvent as in test 1. The sample is considered to have passed if the amount collected in 6 hrs is $<4$ $\mu$g/cm$^2$.

## 9.18 RESISTANCE TO PENETRATION BY BLOOD-BORNE PATHOGENS (ASTM F 1671-97 b)

Protective clothing is required for workers in the healthcare profession to protect them from microorganisms in the body fluids of patients. This is particularly necessary for blood-borne viruses that cause hepatitis (hepatitis B and hepatitis C viruses) and acquired immune deficiency syndrome (human immunodeficiency virus, HIV). This test method assesses the effectiveness of materials for protective clothing used for protection of the wearer against contact with blood-borne pathogens using a simulant microbe suspended in a body fluid simulant. The test equipment essentially consists of a penetration cell ($\sim$60 mL capacity), which is filled with a bacteriophage (a virus that infects bacteria), challenge suspension, and is then pressurized by air. The test specimen (material of protective clothing) acts as a barrier restraining the challenge suspension. Any penetration of the challenge suspension through the test specimen is observed visually at the other side of the specimen from the viewing side of the cell, and viral penetration is estimated by microbiological assay.

The challenge suspension consists of $\phi$X-174 bacteriophage lysate in a nutrient broth. The $\phi$-X-174 virus is not pathogenic to humans, but due to its size, similarity serves as a simulant of blood-borne pathogens including hepatitis B, hepatitis C, and HIV. The nutrient broth acts as a body fluid simulant having a surface tension of 0.042 ± 0.002 N/m. The pressure time sequence specified for the test is 0 kPa for 5 min, followed by 13.8 kPa for 1 min and 0 kPa for 54 min. Any liquid penetration on the other side of the test specimen during the test indicates failure of the sample. After the test period, the outer side of the test specimen is rinsed with a sterile nutrient broth and assayed for test virus by standard procedure. The sample is considered to have passed the test if no $\phi$-X-174 virus is detected in the assay [$<1$ plaque forming unit (PFU)/ml].

## 9.19 ELECTRICAL RESISTIVITY OF FABRICS (AATCC 76-1995)

This test is important as electrical resistivity influences the accumulation of electrostatic charge of the fabric. Besides, this test is also useful for determining the conducting property of metal-coated fabric. The resistance is measured by a resistance meter. Two rectangular flat metal plates of suitable size serve as electrodes. Alternatively, two concentric ring electrodes of spacing suitable to the material can be used. The size of the test specimen should be such as to accommodate the width/diameter of the electrodes. After proper conditioning of the test specimen, the electrodes of the resistant meter are placed on it, ensuring firm contact. The resistance is measured in both length and width directions after steady state is reached, on passage of current. The lower reading in each direction is recorded. The resistivity $R$ in ohms per square is calculated as follows. For parallel electrodes, $R = O \times W/D$ ($O =$ measured ohms, $W =$ width of specimen, $D =$ distance between the electrodes). For concentric electrodes, $R = 2.73O/\log r_0/r_1$ ($r_0$ and $r_1$ are outer and inner radius of electrodes, respectively).

## 9.20 REFERENCE

1. Laboratory methods for evaluating protective clothing system against chemical agents, Mary Jo Waters, Report no. CRDC-SP 84010, CRDC, Aberdeen Proving Ground, MD, U.S.A, 1984.