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KEY ELEMENTS OF PROTECTION FOR MILITARY TEXTILES (BOOK CHAPTER)

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Key elements of protection for military textiles

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Abstract: This chapter discusses the currently recognized critical elements of protection for military personnel. A brief discussion of the history, the current state of the art and expectations for the future for each aspect of protection are given. Aspects of protection considered are limited to threats from human adversaries and include camouflage, ballistic protection and protection from toxic vapors, aerosols and liquids.

Key words: protection, chemical warfare agent, ballistic, aerosol, adsorbent, camouflage.

11.1 Introduction

The cornerstone of apparel, aside from imbuing modern societies with a sense of modesty, is protection. This umbrella term includes protection from the elements: sun, rain, snow, heat, cold, and so forth; from nature: insects, abrasion, irritating flora and fauna, and so forth; and – the subject of this chapter – protection from enemies and their wartime technological equipment, such as improvised explosive devices (IED), small fire arms, toxic chemicals, engineered pathogens, and so forth. However, it should be recognized that it is neither economically nor technologically feasible to protect soldiers completely from all threats. Therefore, a level of acceptable risk must be established that is palatable to upper leadership. In the United States the level of risk is indirectly set by public opinion and, in comparison to most other military powers of the world, the level of risk tolerance remains relatively low. Designing a future military protective ensemble is a juggling act to balance cost and performance, while attempting to predict what the future threat profile will entail. Current systems do not adequately protect personnel and assets against threats developed 75 years ago, much less more recently developed threats. Consequently, action is required in the science community to develop technologies that will define the protective systems that can protect against current and future terrorist and other adversarial actions.

This chapter will discuss the currently recognized critical elements of protection for military personnel, beginning with a brief discussion of the

history. The current state of the art and expectations for the future for each aspect of protection will be addressed.

The primary adversarial threats to soldiers include:

- (a) *Detection* – A soldier does not become a target until he/she is detected. Currently the most widely fielded camouflage for US soldiers consists of a digital screen-print pattern that is called *desert marine* (Fig. 11.1(a)).
- (b) *Wounding by small arms or by shrapnel* – The US military currently uses a ballistic vest system consisting of composite, high-strength para-aramid fibers (Kevlar), and boron carbide ceramic plates wrapped in ultra-high-molecular-weight (UHMW) polyolefins (Spectra™/Dyneema™), as depicted in Fig. 11.1(b).
- (c) *Exposure to toxic chemicals or biological agents* – The US currently uses a suit called the Joint-Service Lightweight Integrated Suit Technology (JSLIST). It consists of a 50:50 nylon–cotton shell fabric with a water-repellent treatment, an adsorbent liner of activated carbon beads, and an internal nylon scrim to protect the carbon liner (Fig. 11.1(c)).
- (d) *Being burned by ignited fuels from IED* – Fire-retardant (FR) textiles are used by select military units. Firefighters wear an FR-treated 100% cotton. Other units wear a woven composite consisting of 65% FR rayon, 25% para-aramid and 10% nylon, marketed as Defender-M™. Note that we will not dwell on FR technologies as they are addressed in detail in Chapter 6.

11.2 Camouflage

Prior to the 1800s military uniforms of Western civilizations were designed to protect soldiers from the elements, to intimidate enemies and to easily differentiate between friend and foe. Thus they were typically brightly colored – the iconic British Redcoat uniforms being the classic example (Kannik, 1968). In the late 1800s, after British troops sustained high casualties in several skirmishes due to the high visibility of their uniform and the use of guerrilla tactics by their adversaries, the British and the majority of Western military organizations adopted drabber colors, and the first vestiges of camouflage began to emerge in modern warfare (Kannik, 1968).

Camouflage is a method of avoiding observation that allows an otherwise visible object to remain indiscernible from the surrounding environment through deception. Traditional military camouflage consisted of combining background pattern matching with disruptive coloration in the form of dye patterns on military uniforms in the visible spectrum to allow soldiers to blend into their surroundings (Behrens, 2009). The widespread availability of infrared spectral imaging, night vision technologies, and more recent advances in hyperspectral and multispectral imaging require that the



11.1 (a) USA fielded camouflage; (b) USA fielded ballistic protection; (c) USA fielded CBW agent protection.

concept of camouflage be applied across a range of electromagnetic (EM) frequencies. In today's modern warfare camouflage represents a critical component of a military combat uniform and represents a soldier's first line of defense – soldiers are not targets until they are seen/detected.

State-of-the-art camouflage is divided into two categories: passive and active or adaptive camouflage. The differentiating factor between these two technologies is that passive camouflage does not adapt to blend in with its surrounding environment as the surroundings change, whereas active camouflage does. Background pattern matching and disruptive coloration are two examples of traditional passive camouflage that represent the most widely used camouflage for modern warfare for more than a century (Behrens, 2009). More advanced and recent developments in passive camouflage include technologies that mask the human body's natural infrared

signature through a combination of photon absorption and EM scattering (NMAB, 2003). These technologies are commercially available and are already integrated into select military garments.

Although fundamental research on adaptive camouflage dates back almost half a century, applied research in the area required breakthroughs in nearly all the fields of science and engineering. Consequently, up until the mid to early 1990s, applied research into active camouflage was largely relegated to the area of science fiction. Today active camouflage is an important area of research for industry, academia and governments. Currently at least one company is already marketing an active camouflage garment that uses a series of flexible organic light-emitting diodes, in addition to EM scattering and absorption techniques, and claims 'invisibility' to infrared, near infrared, and visible EM frequencies (Crane, 2006).

Unlike humans, for whom the idea of active camouflage is relatively new, nature has been in the game for millions of years, which is why many researchers are turning to bio-mimicry for their inspiration. In nature, no species has mastered the skill of active camouflage better than the cephalopods in their use of dynamic iridescence as active camouflage (Birch, 2010). Iridescence is a reflective optical phenomenon that causes the color of a surface to appear to change depending on the angle of incidence of light onto the iridescent material relative to the observer. Examples include the sheen reflected off an oil slick or soap bubble. Although iridescence is common in natural species – pearls, seashells, wings of butterflies and other insects are examples – these do not exhibit dynamic iridescence because they possess no physiological means to control the reflected colors aside from changing the angle of the iridescent surface. Certain cephalopods, however, effectively employ dynamic iridescence through a complex, continual neurophysiological response, whose cycle begins with a visual stimulus and ends with an environmentally adaptive color change (Chiao *et al.*, 2007). In this manner cephalopods keep their 'cloaking device' perpetually on using this active camouflage strategy. Researchers believe that they can mimic this behavior through a combination of electroactive polymers and nanotechnology (Birch, 2010).

Research in the area of metamaterials, or artificial materials that are designed to interact with and control EM waves, takes the prize for stimulating the imagination and generating the most excitement in the quest to develop active camouflage that requires no power. Researchers have theorized, proven and demonstrated that metamaterials can be designed such that they have a negative refractive index over a specific frequency range (Cho, 2006). This means that light falling within this frequency range will literally bend around the object rendering the object invisible from a specific field of view. In theory the phenomenon can be used to bend any wavelength of light, but in practice, because the negative-refractive-index metamaterials

must possess very ordered structures that correspond in size and frequency to the wavelength of light to be bent, it is currently impractical at visible wavelengths. However, researchers say that because visible light possesses a wavelength range between 390 and 750 nm, one can conceive of fabric coated with negative-refractive-index metamaterials – otherwise known as an invisibility cloak (Cho, 2006).

11.3 Ballistics

Another extremely important component of a protective military duty ensemble is protection from small arms fire and fragmentation from grenades, mines and IED. This type of protection is termed *ballistic and fragmentation protection* and its history is extensive. Materials designed to protect against projectile attacks have co-evolved parallel to the development of ballistic delivery methods. In terms of textiles, ballistic protection can be divided into two broad categories: soft, ‘wearable’ armor, wherein the ballistic protection is provided by the soft, flexible textile, and soft–rigid armor, wherein ballistic protection is provided by a combination of inflexible armor plates that are integrated into a high-modulus textile. In this section we will briefly discuss the ballistic protective elements of soft–rigid composite systems, and then delve into research on fully flexible, soft textile systems.

Various levels of ballistic protection exist, and each level is defined in terms of the velocity and mass of the projectile the ballistic armor will protect against. The most widely used standard for ballistics protection for militaries is the ability to stop a 9.6 g 7.62×51 -mm steel jacketed NATO-standard round (US military designation M80) at a velocity of 847 ± 9.1 m/s, which equates to a kinetic energy of 3444 J (NIJ, 2008). This level of ballistic protection is described as Type III, protection from rifle rounds. At this point in time (2010), there exists no commercially available soft system that can provide Type III ballistic protection. There are, however, multiple soft–rigid composite systems that can.

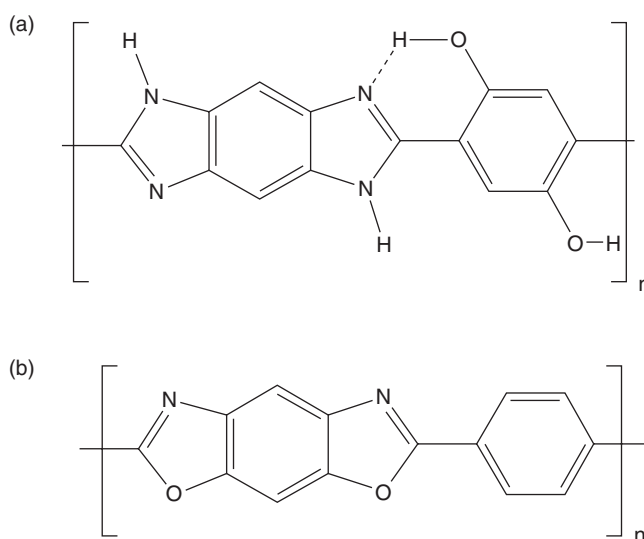
Soft–rigid composite textile systems for ballistics protection typically comprise ceramic armor plates, e.g. boron nitride, tungsten carbide, tungsten disulfide, aluminum nitride, and so forth, coated or contained in high-modulus organic polymers, such as para-aramids e.g. Kevlar™ and Twaron™, or UHMW polyolefins, e.g. Spectra™ and Dyneema™ (NCJRS, 2001). In such systems rigid plates are designed to intercept an incoming projectile and disperse its kinetic energy over a large area, while the soft textile is used to disperse as much kinetic energy as possible and cause deformation of the round prior to it reaching the ceramic plates.

The earliest forms of ballistics protection consisted of multiple layers of metal and hardened, boiled or treated leather components. The commercially

available soft components of anti-ballistics materials of 2010 still consist of layer upon layer of high-strength polymer, and with good reason. These systems rely on their high tensile, specific and shear strength, and elastic moduli to 'catch' an incoming projectile and disperse the kinetic energy as heat over a large area via friction as the polymer chains 'slip' against one another (Northolt and Baltussen, 2001). In materials such as para-aramids and poly(*p*-phenylene-2,6-benzobisoxazole), or PBO, the high elastic moduli are caused by a combination of intermolecular hydrogen bonding and intermolecular *pi* stacking, while UHMW polyolefins, such as DyneemaTM, achieve high moduli through the cumulative Van der Waals interactions resulting from their extremely long polyolefin chains, typically 100 000–250 000 repeating units. UHMW polyolefins are produced by a solvent gel-spinning process (vs. melt-spinning) to produce fibers that are ten times stronger than steel, more durable than polyester, possess a specific strength 40% greater than aramid fibers and are less dense than water (Ward and Ladizesky, 1985). Researchers once hoped that these materials could result in a soft ballistic armor capable of stopping a rifle ballistics round; however, the reliance on the intermolecular kinetic energy dispersion currently prevents this, and thus ceramic plate components are still required to further disperse the kinetic energy over a wider area. While pristine PBO possesses sufficient strength in fiber form to provide Type III ballistic protection in a semi-flexible textile, performance degradation of the polymer via disruption of the intermolecular forces by water, acids and ultraviolet radiation causes unacceptable and unanticipated service life issues (Cunniff and Auerbach, 2003).

Fully flexible soft ballistic protection appears to be on the horizon. Magellan Systems International LLC is working on scaling up production of the high-performance fiber poly{diimidazopyridinylene(dihydroxy)phenylene} or M-5TM. Modeling and simulations predict that M-5TM will perform at least equivalent to pristine PBO without the associated degradation issues. More encouraging is that empirical tests indicate that M-5TM fiber will outperform PBO by a considerable margin (Cunniff and Auerbach, 2003). Researchers attribute the unexpected increase in performance compared to computer modeled predictions to M-5's ability to form hydrogen bonds in the lateral dimension, a trait possessed by no other anti-ballistic fiber. The M-5 fiber's ability to hydrogen bond becomes apparent upon inspection of the structure compared to the structure of PBO, as seen in Fig. 11.2(a) and (b).

Another technology that has demonstrated the ability to serve in an anti-ballistic capacity is a composite system consisting of a high-performance anti-ballistic fiber combined with a shear-thickening colloidal dispersion. Shear-thickening fluids or STFs are liquids whose viscosity increases as a function of applied stress. A mixture of cornstarch and water is the



11.2 (a) Chemical structure of M-5 fiber; (b) Chemical structure of PBO fiber.

classic example of an STF. Researchers at the University of Delaware have produced anti-ballistic yarns possessing STF intercalated into the fiber (Wagner and Brady, 2009). Ballistic tests of these composite fibers show a 250% increase in stopping power of STF-treated Kevlar fibers compared to Kevlar alone. Production of these STF-enhanced textiles for other applications has already begun by Dow Corning under the name Deflexion™. Now, consider a merger of M-5 fiber with STF technology and it becomes apparent that soft anti-ballistic armor will soon be a reality.

11.4 Toxic chemicals

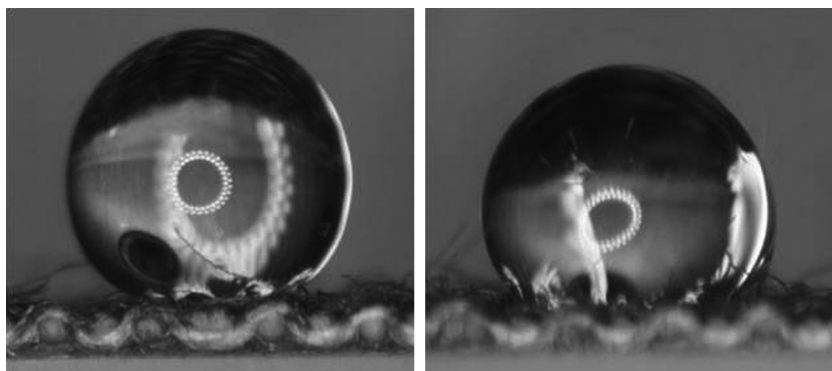
Nobel Laureate Fritz Haber formally introduced the world to chemical warfare at the Battle of Ypres, 22 April 1915 (Cornwell, 2003). The world has not been idle since that time. The dynamic and rapidly evolving science and technology world has driven the threat from newly developed chemical and biological warfare (CBW) agents to new heights (Cordesman, 2001). Moreover, the availability of the Internet and global networking has made it easy and economically feasible for anyone with the inclination and a relatively modest budget to acquire the technology, instrumentation and starting materials to develop both traditional and next-generation threat agents. The challenge lies in developing the capability to deal with the multitude of identified and unidentified threats that will inevitably become available to terrorist organizations and adversaries.

While the enemies' method of choice has traditionally been the use of explosives, events such as the Tokyo subway sarin nerve gas attack, the weaponized anthrax mail attack, and chlorine-laden and fuel-laden IED clearly point to a trend towards CBW (Cordesman, 2001). Unfortunately, while the world of chemistry has advanced exponentially since the 1930s, the systems employed to protect against chemical agents remain essentially the same as they were in the 1930s: passive exclusion barrier materials, such as butyl rubber and poly(vinyl alcohol)s, solid-state adsorbents, such as activated carbon and diatomaceous earth, and hypochlorite solutions for chemical agent decontamination/neutralization (Donahue, 2003). Biological agent protection has come a bit further in the realm of medicine, with the development of new vaccines and antibiotics, but still remains grossly inadequate compared to the wide variety of highly adaptive pathogens available in nature's arsenal, and their availability to practically anyone who has the motivation to use them.

11.4.1 Bulk toxic or burning liquids

Current and past protective ensembles include an outer shell fabric composed of 50:50 nylon-cotton treated with a water-repellent finish. This outer shell fabric represents the first line of defense from incoming threat agents. Unfortunately, in currently fielded systems this shell fabric protects the wearer only from high surface tension liquids such as water. Protection from oils, fuels and other low surface tension liquids – including many chemical threat agents – was and continues (2010) to be provided by the adsorbent activated carbon inner liner. Reliance on the adsorbent liner for protection from bulk liquids is one of the primary reasons why current chemical protective ensembles are heavy, bulky, hot and have a working service life of only 45 days.

By mimicking the surface micro- and nanoscale roughness of the lotus's mantle, the lotus leaf and the rose petal, coupled with surface treatments that allow for much lower surface tensions than found in nature, researchers have demonstrated the ability to repel and prevent the absorption of traditional chemical warfare agents, burning fuels and other liquid threat agents into treated textile materials (Lee and Owens, 2010). The high contact angle to water and oil can be clearly seen in Fig. 11.3. Technologies that can deliver this omniphobic quality on an industrial scale will protect the wearer from a wide range of bulk liquid threat agents and, consequently, allow for lightweight chemical protective ensembles that possess a much longer service life – if this property can be sustained over the lifetime of the garment. According to modern theories of how liquids wet surfaces, such feats are not possible on a permanent basis but are said to exist in a metastable state (Lee and Owens, 2010). However, this 'transient' state appears sufficiently stable across the majority of militarily relevant threat scenarios.

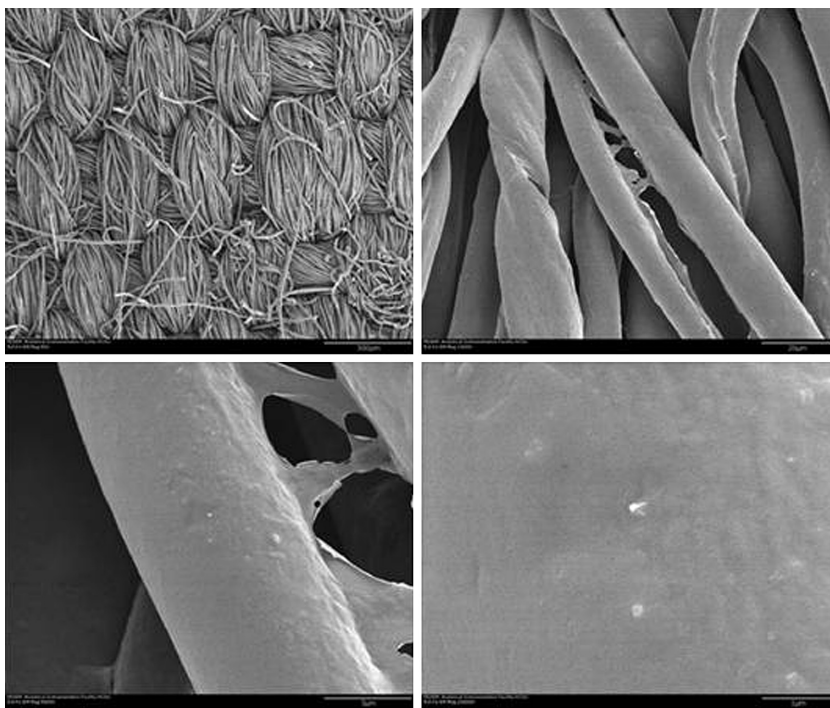


11.3 Left: 5 μ L water droplet on treated 50:50 woven nylon:cotton;
Right: 5 μ L dodecane droplet on treated 50:50 woven nylon:cotton.

Modification technologies are available to change surface energy, structure, morphology, wettability and other physical properties of treated materials. At least three surface modification techniques have demonstrated the ability to produce omniphobic nylon: plasma deposition of perfluoroacrylates, microwave deposition of perfluorosiloxanes, and pretreatment followed by wet processing of nylon using perfluorosiloxanes (Saraf *et al.*, 2010). Such an engineered coating is illustrated in Fig. 11.4, which shows a coating synthesized using microwave deposition. These durable textile treatments are at the forefront of repellent technologies. Textile treatments and modifications are covered in greater depth in Chapter 2 and wetting behavior in Chapters 15 and 16.

11.4.2 Toxic gases and vapors

Another extremely important aspect of chemical protection is protection from toxic gases and vapors. Unlike aerosols, toxic gases and vapors are too small to trap via mechanical filtration and, unless encapsulation technologies are adopted, require removal by either adsorption, absorption, reaction or a combination of these mechanisms. Adsorption is the most commonly used mechanism and is defined as a process that occurs when a gas or liquid solute accumulates on the surface of a solid or a liquid (adsorbent), forming a molecular or atomic film (the adsorbate) (Rolando and Roque, 2007). It is different from *absorption*, in which process a substance diffuses into a liquid or solid to form a solution. Adsorption is operative in most natural physical, biological and chemical systems, and is widely used in industrial applications. Similar to surface tension, adsorption is a consequence of surface energy. In a bulk material, all the bonding requirements (be they ionic, covalent or metallic) of the constituent atoms of the material are filled.



11.4 Scanning electron micrographs (SEM) of microwave-treated 50:50 nylon:cotton.

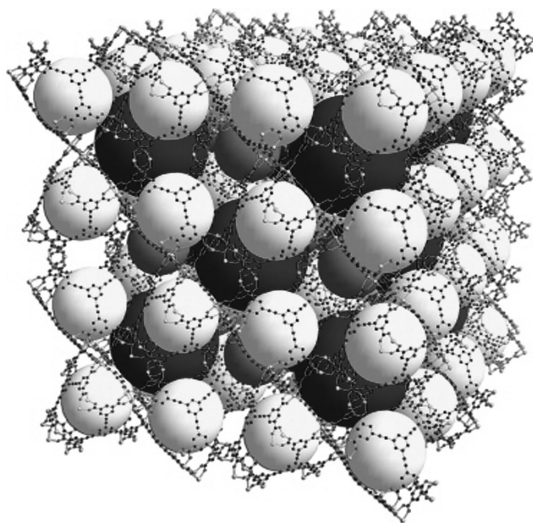
However, atoms on the surface experience a bond deficiency, because they are not wholly surrounded by other atoms. Consequently, it is energetically favorable for these surface features to minimize surface energy by bonding to available compounds. The exact nature of the attachment depends on the details of the species involved, but the adsorbed material is generally classified as exhibiting physisorption or chemisorption. *Physisorption* or physical adsorption is a type of adsorption in which the adsorbate adheres to the surface only through Van der Waals interactions, whereas *chemisorption* is a type of adsorption whereby a molecule adheres to a surface through the formation of a chemical bond, after which a new chemical species is generated (Rolando and Roque, 2007). Unfortunately, physisorption is most common in activated carbon, the most commonly used adsorbent for protection from toxic vapors. Desorption of physisorbed vapors is reversible and is dependent on the mass transfer rate into and out of the adsorbent and on the affinity of the adsorbate for the adsorbent. The mass transfer equilibria of such systems are highly variable depending on the concentration of the target compound in the air vs. concentration of the target compound in the adsorbent, on temperature, and on competitive kinetics of interferents

(e.g. commonly encountered solvents, pesticides, diesel exhaust, fuel vapors, etc.) (Rivin and Kendrick, 1997). Additionally, such systems can reach their saturation point, at which stage they have exhausted their adsorbent capacity for the target compound. The high variability within these materials, coupled with the huge numbers of unknown variables in a practical environment make it extremely difficult to predict the amount of time these systems will function properly before needing to be replaced; consequently, extremely conservative parameters have been established that govern the system's working life based on worst-case environmental conditions.

Because they possess extremely large surface areas per unit weight, activated carbon, silica, alumina and zeolites are the most common commercially available adsorbents. Just one gram of activated carbon has a surface area of 500–1000 m²/g (for comparison, a tennis court is about 260 m²). Activated carbon is produced by pyrolysis and carbonization of organic matter, typically coconut shells or hardwoods. Silica gels are matrices of hydrated silicon dioxide, alumina is mined or precipitated aluminum oxide and hydroxide, and zeolites are highly ordered aluminosilicates that occur naturally and can be synthesized. Activated carbon composite beads are currently used in most chemical warfare agent protective ensembles.

Research in novel adsorbents for protection from toxic vapors has taken two converging directions. One direction involves the development of catalytically reactive adsorbents, wherein the adsorbent decomposes the toxic vapor before it can penetrate the textile. Such an approach has the advantage that the adsorbent no longer needs to prevent breakthrough of the toxic chemical, but only to react with the toxic vapor faster than it can penetrate the adsorbent liner. Literally thousands of reactive adsorbents have been evaluated, but most fall into one of three categories based on mode of decomposition: hydrolysis catalysts, oxidation catalysts and degradative enzymes (Yang *et al.*, 1992). Two major drawbacks of such an approach are that decomposition products are not always non-toxic, and not all toxic vapors undergo the same decomposition pathway or at the same decomposition rate. Thus such systems must be targeted to specific threat agents, typically traditional chemical warfare agents. Unfortunately recent wartime activities suggest that such a narrow approach may be flawed. Consequently, the area of reactive adsorbents is rapidly converging with the development of ultra-high-surface area (UHSA) adsorbents.

Research in UHSA adsorbents is primarily concentrated in the area of highly periodic crystalline structures called metal–organic frameworks or MOFs. An MOF is composed of two major components: a metal ion or cluster of metal ions and an organic linker molecule. An MOF cage filled with adsorbate is shown in Fig. 11.5, clearly depicting the extremely high pore volume and open structure. The organic units are typically multivalent ligands. The choice of metal and linker govern the structure pore geometry,



11.5 Pictorial representation of an MOF filled with adsorbate.

and stability of the MOF (MacGillivray, 2010). This versatility allows for tailored design of MOFs based on desired application. These structures possess theoretical surface areas of $>8000 \text{ m}^2/\text{g}$ – more than five times the surface area of the best activated carbon!

11.4.3 Aerosols

Traditionally military protective textiles do not provide significant percutaneous protection from liquid or solid aerosolized particles. However, with the development of new CBW agents, new dispersion techniques, the use of toxic industrial materials as threat agents, and the threat of bombs laden with radioactive dust, referred to as ‘dirty bombs’, percutaneous protection from aerosols has become a critical aspect of future military protective textiles (Cordesman, 2001). The current goal for aerosol protection is achieving aerosol protection without significantly affecting water vapor transport.

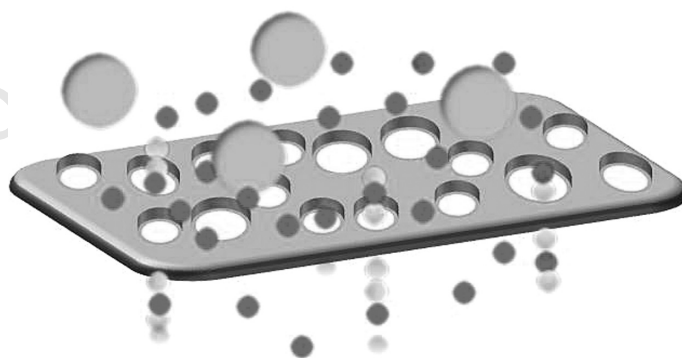
Currently two approaches exist for providing percutaneous aerosol protection: encapsulation and mechanical filtration. Encapsulation, the oldest and crudest form of protection from aerosols and poisonous chemicals, consists of covering the area to be protected with a material that is non-porous, and therefore impermeable to aerosols. While this approach does protect personnel from aerosols and other poisonous threat agents, it also encumbers the wearer with an unacceptable thermal burden that will likely result in more harm than good – note that the majority of both wartime and peacetime casualties in the past 30 years have been heat-stress related. Nonetheless, if the need arose, commercially available encapsulation

technologies are available and include a number of impermeable materials such as butyl rubber and polypropylene suits. As, by definition, encapsulation techniques allow for no improvement in breathability, we will focus primarily on advances in mechanical filtration technologies.

Mechanical filtration, which is defined as the physics of the interactions between fine particles and airstreams with filter fibers, membranes and surfaces, is well understood (Davies, 1973). Particle motion in an air stream depends on the characteristics of the particle and for a typical particle having a density near 1.0 g/cm^3 inertial motion dominates at sizes larger than one micrometer, while diffusional processes dominate at sizes smaller than 100 nm. Aerosols of $<500 \text{ nm}$ typically agglomerate via Brownian coagulation and electrostatic interactions with other aerosols to form particles of $>1 \text{ }\mu\text{m}$. The ability of an aerosol to stay airborne is a function of its mass, inertia, velocity and the velocity and turbulence of the air that the aerosol is suspended in, which can be calculated using the Navier–Stokes equation. In general, aerosols larger than $8 \text{ }\mu\text{m}$ in diameter exhibit rapid gravitational settling in most relevant military scenarios (Hinds, 1999). Therefore, the primary aerosol threat for textiles is in the size range of about 20 nm – $7.0 \text{ }\mu\text{m}$.

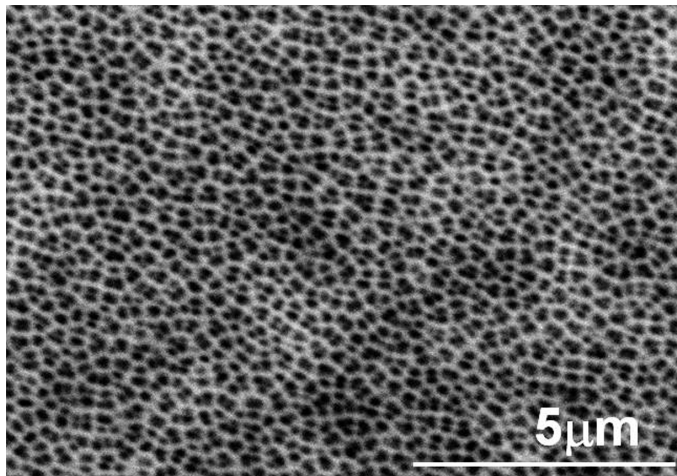
The area of mechanical filtration lends most of its advancements to removal of particles from gases, primarily air, and liquids, primarily water. Mechanical filtration technologies that are adapted for integration into a wearable textile include membrane technologies, fibrous filtration technologies and hybrids that possess aspects of both fibrous and membrane particulate filtration.

A membrane, as defined by the International Union of Pure and Applied Chemistry (IUPAC), is a structure having lateral dimensions that are much greater than its thickness, through which mass transfer may occur under a variety of driving forces – or, from our perspective, a thin sheet of material that is mostly solid, with intermittent holes as in Fig. 11.6 (IUPAC, 1996).

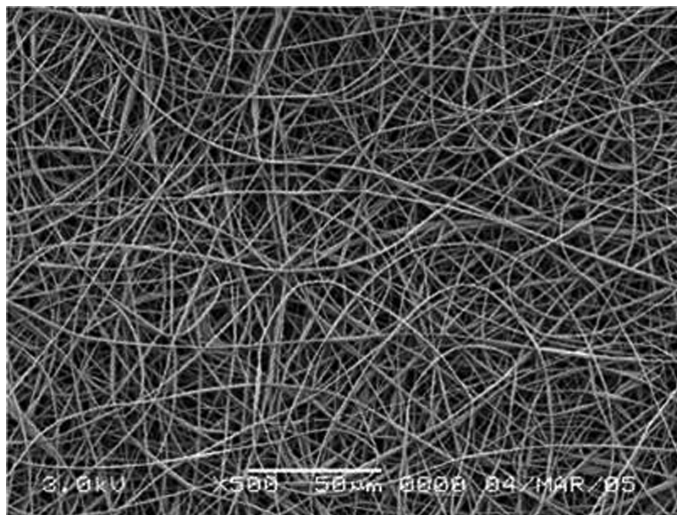


11.6 Pictorial representation of a size exclusion membrane.

Common commercially available, wearable membrane technologies include expanded polytetrafluoroethylene composites, e.g. Gore-tex™, and polyether ether ketone (PEEK) composites. As in the case of encapsulation, the very definition of a membrane – a structure having lateral dimensions much greater than its thickness – significantly limits the rate of mass transport through the membrane. Figure 11.7 shows an actual membrane for comparative purposes with Fig. 11.8. While a membrane serves well from an aerosol protection sense, it makes maintaining adequate water vapor transport difficult.



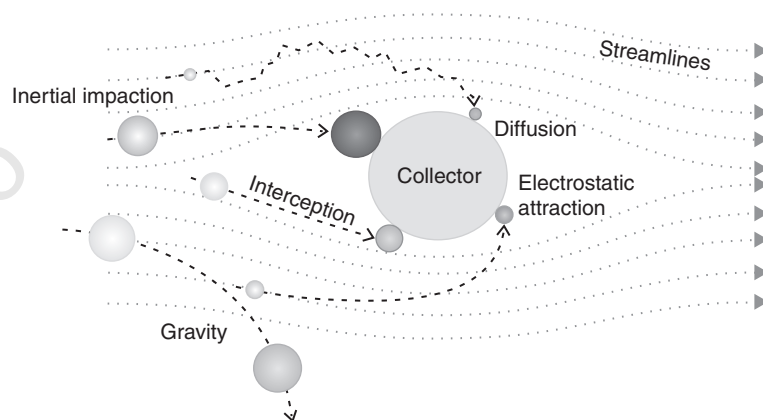
11.7 SEM of an alumina membrane.



11.8 SEM of meltblown glass fiber aerosol filtration media.

Traditional fibrous aerosol filters partially circumvent the water vapor transport difficulty by increasing the air space between individual fibers and relying more heavily on mechanisms other than size exclusion for achieving performance. Fibrous aerosol filters are typically composed of a mat of randomly arranged fibers wherein the air space between individual fibers is typically much greater than $0.3\text{ }\mu\text{m}$. Key factors affecting the function of fibrous filters are fiber diameter, filter thickness, face velocity and electrostatic surface charge. The intuitive assumption that a high-efficiency filter functions based solely on size exclusion, allowing particles smaller than the largest opening to pass through, is incorrect. Unlike membrane filters, in which particles as wide as the largest opening or distance between fibers are prevented from traversing the pore, fibrous high-efficiency filters can capture aerosols that are much smaller than the distance between fibers by relying more on interception, diffusion, and electrostatic attraction than on size exclusion or inertial impaction for capturing submicron aerosols. Consequently, fibrous filters are typically much more open than membranes. Figure 11.9 illustrates the combination of mechanisms a fibrous high-efficiency filter employs for capturing aerosols. The four primary mechanisms of aerosol capture are (Hinds, 1999):

1. *Interception* – Particles following a line of flow in the air stream come within one radius of a fiber and adhere to it.
2. *Inertial impaction* – Larger particles are unable to follow the curving contours of the air stream, run into a fiber and stick to it; this mechanism increases in efficiency with diminishing fiber separation and higher air flow velocity.
3. *Diffusion* – The collision with gas molecules by the smallest aerosol particles, especially those below $0.1\text{ }\mu\text{m}$ in diameter, which are thereby



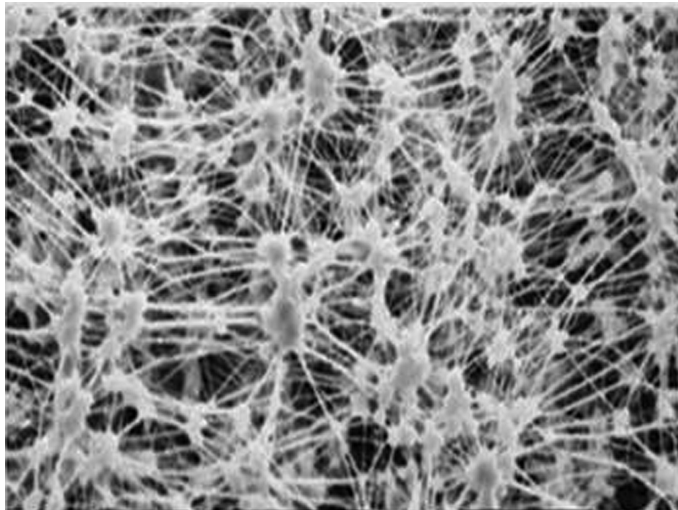
11.9 Pictorial representation of the mechanisms of aerosol capture.

deflected out of the streamline in their path through the filter and onto a fiber. This behavior is similar to Brownian motion and raises the probability that a particle will be stopped by either of the two mechanisms above. Diffusion becomes the dominant capture mechanism at smaller particle sizes, and is more efficient at lower airflow velocities.

4. *Electrostatic attraction* – Particles adhere to a surface due to the build-up of static charge on the *surface* of objects.

Aerosol filtration media created by stretching or expanding membranes so as to dramatically increase the size and volume of their pores are also commercially available. These technologies are essentially fibrous filtration media that are derived from membranes (Fig. 11.10). Commercially available fibrous aerosol filtration methods that can be integrated into a wearable textile are numerous because any technology that can durably deposit a fibrous mat onto a textile represents an improvement to aerosol penetration. Again, as previously stated, the difficulty is providing adequate aerosol protection without significantly reducing the overall breathability of the textile. To accomplish this researchers are turning to nanoscale fibrous materials.

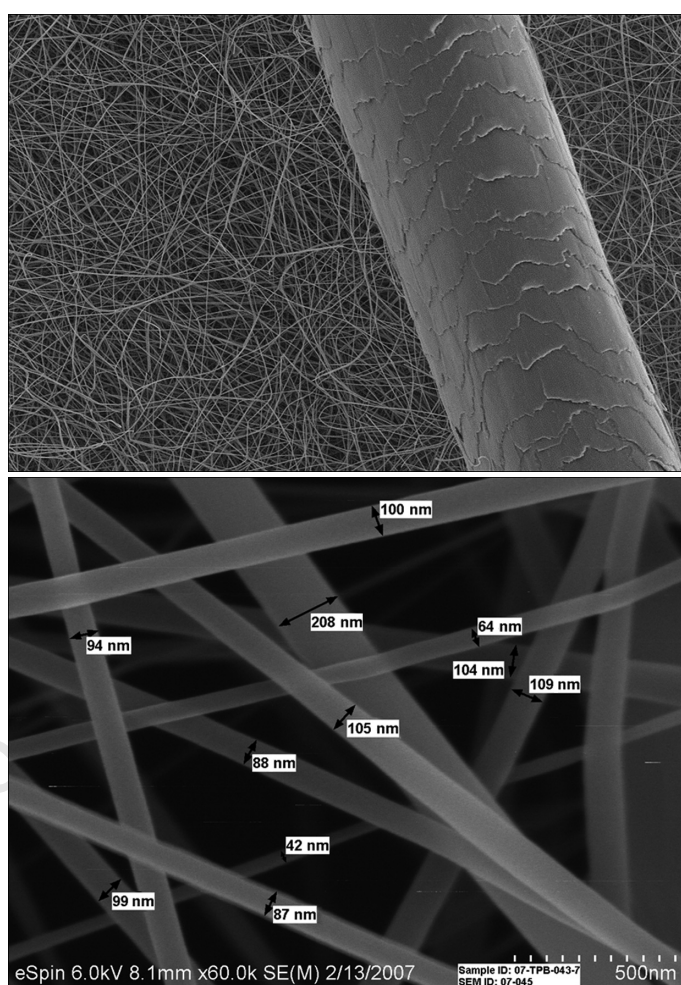
Research in the area of nanotechnology for producing nanoscale aerosol filtration media is currently at the leading edge of research in textile incorporable aerosol filtration. This is because as fiber diameters approach the mean free path of air, 35–65 nm, the mixture of molecules that comprise air enter into the slip-flow regime with respect to passage through the filtration



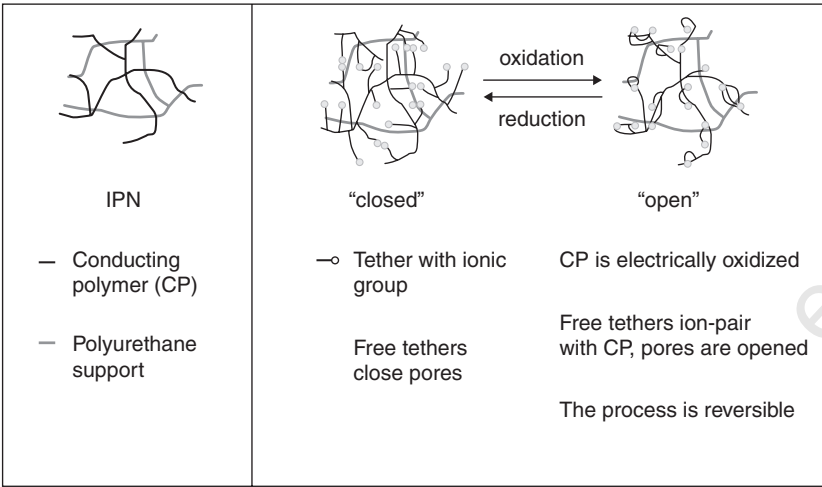
11.10 SEM of expanded polytetrafluoroethylene.

media (Fig. 11.11(a) and (b)). This means that air and water vapor can pass nearly unhindered through the filtration media while larger molecules and aerosols cannot. Several methods exist for producing submicron fibrous media, such as electrospinning, islands-in-the-sea extrusion, bacterial synthesis, growth of nanoscale inorganic oxides onto supports, and so forth; however, the durability of these delicate nanoscale structures for flexible textile applications is questionable and is currently under investigation.

One of the most ambitious, cutting-edge research efforts to protect from aerosols and liquids involves a marriage of electrochemistry and mechanical filtration. While approaches to achieving 'smart' textiles like the one



11.11 (a) SEM of an electrospun web compared to a human hair;
(b) High-resolution SEM showing the nanoscale diameter of the fibers.



11.12 Pictorial representation of a conducting interpenetrating fibrous network in its closed state (a) and open state (b). Figure courtesy of Dr. Banahalli Ratna, Naval Research Laboratory.

described here are discussed in greater depth in Chapters 3, 7 and 10, the focus of this effort necessitates a brief description here. The project, managed and directed by Dr. Banahalli Ratna at the Naval Research Laboratory, has developed an interpenetrating network (IPN) material (Fig. 11.12) composed of soft polyurethane interspersed with a conducting polymer network that can be reversibly switched between two conducting states by the application of a small potential (~ 1.0 V). The switchable states allow charged tethers to form complexes within the conducting polymer portion to either increase the material’s porosity, or decrease it, on command. Chemical warfare protective clothing, or partial clothing sections, formed from this material will have normal permeability (breathability) for comfort while at the same time have the ability to instantaneously and reversibly lower their permeability to agent molecules by application of the small voltage. When the membrane is in its ‘closed’ state, it will block the transport of threat agents. When the threat is removed, a second voltage application will ‘switch’ the membrane to its ‘open’, breathable state. The open state allows the wearer comfort with low heat load, and rapid moisture vapor transport away from the body.

11.5 Conclusions

An ideal military protective ensemble would incorporate protection from detection, ballistics, toxic aerosols, toxic liquids and vapors, possess fire-retardant qualities, breathe like cotton, and be machine washable. Obviously

overcoming one deficiency is difficult in its own right, so when presented in bulk as an integrated system, the task might seem impossible. However, after the subtasks are separated and distributed into their respective areas, one can see that considerable progress is occurring in every facet of protection. To the skeptics that claim a wholly integrated protective system is impossible, I offer an old idiom: 'How do you eat an elephant? One bite at a time.'

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