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4.1 Introduction

Technological advances in the field of technical or high performance textiles have made it possible to engineer materials designed to meet specific needs. However, there is no ‘ideal’ fabric that will provide protection against all hazards. Careful selection of appropriate textiles is crucial for the performance, use, care, and maintenance of protective clothing. Broadly, a clear understanding of the work environment and performance requirements as well as knowledge of the textiles, is essential for the decision making process. According to the OSHA Technical Manual, ‘In general, the greater the level of chemical protective clothing, the greater the associated risks. For any given situation, equipment and clothing should be selected that provide an adequate level of protection. Overprotection as well as under-protection can be hazardous and should be avoided’.\(^1\)

The above statements are also applicable to other types of protective clothing. Heat, physical and psychological stress, as well as reduced dexterity and mobility, are examples of additional hazards that may be a result of the use of protective clothing. In addition to protection, the selection of textiles takes into consideration factors such as the impact of protective clothing on job performance; comfort; durability; availability and cost; use, care, and maintenance, and cultural factors. To select protective clothing materials, relevant factors have to be identified and prioritized in a multi-step process. It is imperative that such a holistic approach be taken while selecting materials for protective clothing. Basing the decision on just the performance properties of the material may result in low user acceptance. For example, a glove that protects a surgeon may be rejected if it hinders the surgeon’s ability to operate effectively.

This chapter presents a model of the decision-making process and gives some examples of the level of detail necessary in each step. In addition, it describes an online system as a case study to illustrate how technology can be used to assist in the selection of textile materials for protective clothing. The scope of this chapter is limited to the selection of protective clothing materials and not the
entire assembly. It is important to note that while careful selection of suitable materials is crucial for the performance of the clothing ensemble, testing of just the materials is not sufficient to determine the performance of the ensemble, especially for multi-component and fully encapsulating suits. Part II includes the performance of clothing ensembles for selected end uses.

The selection of textile materials requires a step-by-step approach in which the potential hazard is clearly defined, and the material is selected in accordance with the existing standards or guidelines. If no standards or guidelines are available, relevant test methods must be identified and used. This initial screening, based on protection provided by the material against potential hazard, is used to narrow the choices. Factors other than protection are then considered to make the final selection. Figure 4.1 provides a model of the selection process discussed in this chapter.

4.1 Recommended steps in the selection of textiles for protective clothing.
4.2 Assess hazards

The hazards, as well as a scenario that includes the work environment, are used to define potential risks to the individual. Hazards and scenarios to assist in the selection of materials are very well defined in some sectors, but in other sectors there may not be such well defined scenarios. In general, well defined risk scenarios and performance specifications based on the risks are available for sectors where the use of protective clothing is crucial for the safety of the individuals. For example, selection of protective clothing for firefighters and police is based upon well developed scenarios and requirements. With increased risk of terror attacks, the work scenarios for police and firefighters have changed in countries such as the United States, and the new risks impact the guidelines, standards, and selection of protective clothing materials. These new risks may also require the development of new materials that provide additional protection to such individuals. With the change in work scenario, firefighters and other professionals who are now categorized as ‘first responders’ need protection against other hazards. The United States Department of Homeland Security has adopted personal protective equipment (PPE) standards developed by the National Institute for Occupational Safety and Health (NIOSH) and the National Fire Protection Association (NFPA) to protect first responders against chemical, biological, radiological, nuclear, and explosive (CBRNE) threats.

In case of serious new threats, decisions regarding protective clothing may have to be made in a very short time frame. For example, decisions had to be made immediately regarding selection of appropriate personal protective equipment for protection against viruses such as severe acute respiratory syndrome (SARS) and anthrax. In those two scenarios, assessing the hazards was the crucial first step in the selection of the protective clothing.

4.2.1 Type of hazard(s)

The types of hazards are broadly classified as chemical, biological, physical/mechanical, radiological, and flame and thermal. This classification is used by national and international standards organizations as a framework for organizing their committees and for related publications regarding terminology, standards, and performance specifications. Limited information is available regarding protective clothing against radiological hazards due to the nature of the hazard. The current approach is to incorporate detecting devices to warn individuals of the hazard and thus prevent them from being exposed. The ASTM F23 Committee on Protective Clothing has recently established the F23.70 Radiological Hazards subcommittee to address issues related to radiological hazards.

Factors such as composition and physical form of the hazard are used to further categorize each type of hazard. Given below are the common sub-
categories for each of the main types of hazards. Chemical hazards are categorized by the chemical composition, physical form, and toxicity. They are commonly identified by the common name, the Chemical Abstract Registry Service (CAS) number, and the chemical class to which they belong. The CAS numbers are numerical unique identifiers assigned to each substance. Chemicals from the same class, in general, have similar chemical composition. Thus, some commonly used chemicals from the various classes are used to determine the performance of materials against a broad range of chemicals. In cases such as pesticides where mixtures are used, it is recommended that the performance be measured against a representative mixture, rather than determining the performance based on a broad range of chemicals. The chemicals have different physical forms – solids, liquids, aerosols, and gases. The tests used to determine the performance are often determined by the physical form and the severity of the hazard. Additional information is included in section 4.4.1.

Biological hazards are divided by the type of microorganism and the mode of contamination. In the medical field, the primary potential risk to the individual is exposure to hazardous bacteria and viruses through contact with contaminated blood and other potentially hazardous body fluids. Surrogate microbes are commonly used to assess the penetration of extremely hazardous substances such as Hepatitis (B and C) and Human Immunodeficiency Viruses. The other risk is exposure to hazardous airborne pathogens such as influenza and the SARS viruses. Airborne pathogens may pose a risk to the general public, in addition to medical personnel. The hazard may be due to natural causes or as a result of bio-terrorism. As the use of biological agents poses a threat in wars, protective clothing materials are also used to protect military personnel.

Physical hazards, categorized by the type of contact of the object with the material, can be broadly divided into cut, ballistic, puncture, and abrasion. Cut injuries occur in work environments where individuals work with sharp, high-speed objects such as chainsaws. In most cases, resistant materials are used to protect the hands and legs. Ballistic protection is required to protect individuals from bullets. Bullets may also cause blunt trauma injury by deforming the body armor. Thus, body armor designed to protect individuals is evaluated for ballistic protection as well as the ability to prevent blunt trauma injury. Puncture or stab resistance is required to protect individuals from sharp objects such as knives, as well as comparatively blunt objects commonly used by inmates in correctional facilities. In addition to the above mentioned hazards, protection against abrasion is also used as a criterion for selecting the material. Protection against multiple physical hazards is commonly required for individuals in the military, police force or correctional institutions. Body armor is commonly used to provide protection against physical hazards. Puncture resistance tests are conducted on numerous fabrics that provide protection from hazards such as radiological and biological protection, as the individuals may be exposed to other hazards, if the material is punctured by a sharp object.
Flame and thermal hazards are grouped by the source of flame or heat. The most common types of hazards are exposure to open flame, radiant heat, and molten material. Individuals such as firefighters are susceptible to the potential of burn as a result of exposure to open flame and radiant heat. Individuals working in industries where they are exposed to molten metal need materials which reduce burn injuries by shedding molten metal into the floor.

4.2.2 Severity of the hazard

The toxicity of the hazardous material, duration of exposure, and level of exposure are used to determine the severity of the hazard. All three factors are interrelated and should be considered as a set. For all categories, toxicity of the materials and the by-products are the primary concern. Highly toxic substances or hazardous conditions have to be handled with extreme care in all categories, regardless of the duration and level of exposure. The level of exposure and the duration of exposure are considered with reference to the toxicity. For example, exposure to even a small amount of a chemical agent for a short duration may be far more harmful than exposure to a Class IV pesticide while spraying for an entire work day.

For many end uses, PPE is rated based on the severity of the hazard. For example, body armor classification developed by the National Institute of Justice (NIJ) is used for the selection of the body armor based on the potential workplace hazard. European Union certification for PPE uses Type I-VI categories that are based on very broad hazard scenarios. Although there are ratings or classifications for the various types of hazards, there is no universal system to rate the severity of all hazards. In the future, there may be a system to assess the severity and rate it regardless of the type of hazard. For example, the extremely hazardous category may be defined to include all hazard scenarios that are life threatening in very small amounts. Thus, the extremely hazardous category may include SARS and anthrax from the biological category, nerve gas from chemical, ballistic from physical, and radioactive materials from radiological hazards. This type of rating would help in the testing and selection of PPE materials. For example, when the severity of hazard is extreme, stringent rules would apply for the handling and testing of fabric, and thorough testing of the whole garment ensemble would be necessary.

4.3 Identify relevant standards, specifications or guidelines

Regulatory standards, performance specifications, guidelines, and test standards established by national and international standards organizations, governmental agencies, as well as associations for various professions are available to determine performance and assist in the selection of the textile materials.2–6
Regulatory standards are often mandated by governmental agencies as well as other organizations that have jurisdiction for a particular group. Knowledge of the performance specifications and standards is essential. Often companies that manufacture materials and protective clothing may have to comply with more than one set of requirements, as these may vary by geographic locations. For example, due to differences in minimum specifications as well as the required test methods, garments may meet the requirements in the United States but not in the European Union or vice versa. Thus, it is not unusual to find different products being marketed by the same manufacturer in different countries.

The specificity of the regulations and standards varies considerably. They range from very clearly defined selection, use, care, and maintenance criteria for personal protective equipment (PPE) to requirements in which the employer is responsible for providing ‘appropriate protective clothing.’ In some cases there is either no performance standard or guideline, or they are in the process of being established. Given below are examples of standards and specifications for different scenarios and the impact they have on the selection process for the particular hazard.

4.3.1 Standards with well defined tests standards and performance specifications

Protection of Industrial Personnel against Flash Fire: The NFPA 2112 Standard for Flame-Resistant Garments for Protection of Industrial Personnel against Flash Fire and NFPA 2113 Standard on Selection, Care, Use, and Maintenance of Flame-Resistant Garments for Protection of Industrial Personnel against Flash Fire are standards established by NFPA International. These standards have clearly defined test methods and minimum requirements that assist in the selection of protective clothing materials. The manufacturers of the materials often provide data to guide product selection. Well defined standards, performance specifications, and guidelines that specify minimum performance requirements are very beneficial in the selection process, as they allow the individual responsible for selection to be able to compare the performance characteristics as well as other factors that play an important role in choosing the best material for the end use.

4.3.2 Standards with no tests standard and performance specification defined

The PPE standard mandated by the U.S. Occupational Safety and Health Administration (OSHA) for occupational exposure to blood and other potentially infectious materials is applicable to a wide range of scenarios. According to the standard, the employer is required to provide ‘appropriate’ personal protective equipment (PPE) for the employees. However, the test method and the
minimum requirements are not specified. It is thus the responsibility of the employer to determine the hazard and select appropriate PPE to protect the employees at work. As the regulations do not provide guidelines on the types of test or material to be used, it is up to the manufacturer to determine the test method to evaluate the performance of their materials and up to the employers to select the materials suitable for their end uses. Standards with no test method and minimum requirements pose a major problem in the selection of suitable materials, often resulting in over or under protection of the individuals.

4.3.3 Standard with recommendations based on garment design and not performance

Requirements for PPE for pesticide applicators in the United States are currently based on garment design and not on the performance of the garments. Test results show that the penetration of pesticides through garment materials in the same category varies considerably. Thus, recommendations such as use of long sleeve shirts and pants, commonly seen as part of the safety instruction on a pesticide label, are not sufficient.\textsuperscript{9} Basing the recommendations on just garment design may result in over or under protection of the individuals. A task force has been formed as part of ASTM-F23 Committee for Protective Clothing to develop performance specifications for protective clothing during pesticide application.

4.4 Screen materials based on protection performance

The specificity of the standards, performance specifications, and guidelines determines the tests required to assess protection performance of the materials. For end uses where the hazard and minimum requirements are clearly defined, test data is usually available through fabric and garment manufacturers. Compliance of the material and garments with relevant standards is also commonly posted on the manufacturer’s website.\textsuperscript{10-13} In situations where regulations do not specify the test methods, or there is no performance specification, the individual responsible for selecting the protective clothing has the added responsibility of determining the scenario and test method suitable for assessing the performance of the materials. Often the appropriate test method will have to be selected. A clear understanding of the exposure scenario that includes type, level, and duration of exposure, and environmental conditions is essential. The information should be used to identify the standard that represents the scenario of the proposed end use. Often the test methods allow for testing at different levels of severity and/or duration of exposure. Defining the potential scenario is helpful in selecting the appropriate parameters for testing. In some cases, the method may have to be modified if the test parameters and procedures are not adequate to test for the potential scenarios.
As there are many probable scenarios, several test standards have been developed for each of the broad hazard categories. It is not unusual to find two or more test methods developed by different groups to measure the same end use performance. The results from the test methods may be similar or may vary considerably depending on the scenario or the basis for the test method. For example, three national and/or international standards are used to measure the penetration of liquid pesticides. Comparison of the three methods showed major differences in the pesticide penetration values for the same materials. This was due to the fact that the scenario or the basis of the test method ranged from simulation of accidental spill to fine spray.

Given below is information regarding selection of materials based on protection performance against the broad categories of hazards. The categories and examples used are not all inclusive as there are numerous scenarios within each of the categories. The purpose of this detail is to illuminate the level of complex analysis needed.

### 4.4.1 Chemical protection performance

The route of entry into the body determines the type of protection required. For example, face masks or respirators with different filters are used to protect individuals against exposure due to inhalation. Chemical protective clothing is used to protect against dermal exposure. Chemical protective clothing materials are broadly divided into woven; nonwoven; laminated to microporous or hydrophilic membranes; coated, bonded, or laminated with plastic films or rubber; and films, sheets, or moulded plastic or rubber. The performance of the chemical protective materials varies considerably based on the air permeability, chemical composition, and material characteristics. Penetration, permeation, and/or degradation of the materials are measured to determine the chemical resistance. In general, the physical form of the chemical that poses a potential risk and the type of material determine whether penetration, permeation, and/or degradation tests have to be conducted. Permeation is ‘the process by which a chemical moves through a protective clothing material on a molecular level. Permeation involves (i) sorption of molecules of the chemical into the contacted (challenge side) surface of the material; (ii) diffusion of the sorbed molecules in the material, and (iii) desorption of the molecules from the opposite surface of the material’.

The permeation rate and breakthrough time are important for measuring permeation. Permeation tests are conducted to determine the performance of non-porous materials such as monolithic films against volatile and non-volatile liquids and gases. It is not used to measure the performance of woven or knitted fabrics. For such porous materials, penetration tests are used to measure performance. Penetration is defined as the ‘process by which a solid, liquid, or gas moves through closures, seams, interstices, and pinholes or other
imperfections on a non-molecular level, in a protective clothing material or item. Penetration through a material can be measured by several national and international standards. The selection of a suitable standard depends on the exposure scenario. For example, there are three national and international test methods to measure the penetration of pesticide through textiles. Degradation is defined as ‘a deleterious change in one or more properties of a material’.

Materials that have degraded due to chemical exposure, use or exposure to environmental conditions such as sunlight should be discarded, as these affect the fabric performance.

Given below are the ASTM, ISO and EN test standards used to evaluate performance of materials against chemical hazards. In addition to the test methods stated below, national and international standards are also used to measure the performance of whole body ensemble.

- ASTM F1186-03 Standard Classification System for Chemicals According to Functional Groups.
- ASTM F1001-99a Standard Guide for Selection of Chemicals to Evaluate Protective Clothing Materials.
- ASTM F739-99a Standard Test Method for Resistance of Protective Clothing Materials to Permeation by Liquids or Gases Under Conditions of Continuous Contact.
- ASTM F1383-99a Standard Test Method for Resistance of Protective Clothing Materials to Permeation by Liquids or Gases Under Conditions of Intermittent Contact.
- ASTM F1407-99a Standard Test Method for Resistance of Chemical Protective Clothing Materials to Liquid Permeation-Permeation Cup Method.
- ASTM F1194-99 Standard Guide for Documenting the Results of Chemical Permeation Testing of Materials Used in Protective Clothing.
- ASTM F903-03 (2004) Standard Test Method for Resistance of Materials Used in Protective Clothing to Penetration by Liquids.
- ASTM F2053-00 Standard Guide for Documenting the Results of Airborne Particle Penetration Testing of Protective Clothing Materials.
- ASTM F2130-01 Standard Test Method for Measuring Repellency, Retention, and Penetration of Liquid Pesticide Formulation through Protective Clothing Materials.
- EN 943-1:2002 Protective clothing against liquid and gaseous chemicals, including liquid aerosols and solid particles – Part 1: Performance requirements.
- EN 467:1995 Protective Clothing – Protection against liquid chemicals – Performance requirements for garments providing protection to parts of the body.
- EN374-3:1994 Protective gloves against chemicals and micro-organisms – Part 3: Determination of resistance to permeation by chemicals.
Steps in the selection of protective clothing materials

- EN ISO 6529 Protective clothing – Protection against chemicals – Determination of resistance of protective clothing materials to permeation by liquids and gases.
- ISO 6530 (1990) Protective clothing – Protection against liquid chemicals – Determination of resistance of materials to penetration by liquids.
- ISO 13994 (1998) Clothing for protection against liquid chemicals – Determination of the resistance of protective clothing materials to penetration by liquids under pressure.
- ISO 17491 (2002) Protective clothing – Protection against gaseous and liquid chemicals – Determination of resistance of protective clothing to penetration by liquids and gases.
- ISO 22608 (2004) Protective clothing – Protection against liquid chemicals – Measurement of repellency, retention, and penetration of liquid pesticide formulations through protective clothing materials.

Permeation data is generally available for commonly used chemical protective clothing materials. Breakthrough time, the time taken by the chemical to pass through the material, is commonly used to measure permeation. In addition, permeation rate, which is the rate at which the chemical moves through the material, is also recorded. Chemical resistance data can be obtained from published guidelines as well as from manufacturers of the chemical protective clothing. ‘Guidelines for the Selection of Chemical Protective Clothing’ and ‘Quick Selection Guide to Chemical Protective Clothing’ include color-coded recommendations for sixteen commonly used barrier materials. The color codes and corresponding breakthrough times used in the guidelines are green for breakthrough detection time of >4 hours of continuous contact (a >8 is used when the breakthrough is greater than eight hours); yellow with breakthrough detection time between 1–4 hours; red with breakthrough times of less than one hour. White is used when no data is available for the material. Testing the material against the challenge liquid is recommended prior to use. Contact between the material and the chemical may result in degradation of the material or the breakthrough may be a result of the degradation of the material. It is important to note that the data reported in the guidelines is a compilation of published and unpublished permeation test data obtained from various sources. The authors of the publication state that at least 90% of the tests were conducted using ASTM F739-99, Standard Test Method for Resistance of Protective Clothing Materials to Permeation by Liquids or Gases Under Conditions of Continuous Contact. The majority of the data for generic materials is a summary of results from different sources. According to the OSHA technical manual, ‘The major limitation for these guidelines are their presentation of recommendations by generic material class. Numerous test results have shown that similar materials from different manufacturers may give widely different performance. That is to say manufacturer A’s butyl rubber glove may protect against chemical X, but a butyl glove made by manufacturer B may not’.1
A majority of manufacturers test the materials against a battery of liquid and gaseous chemicals, which represent a wide range of commonly used chemicals in different classes. Often the recommended chemicals published by national and international standards organizations are used by the manufacturers as a common group of chemicals. The recommended list of challenge chemicals as well as the chemical class that is published by ASTM International is included in Table 4.1.\(^7\) The performance data, based on tests conducted by independent laboratories, is publicly available through a manufacturer’s website. This data is specific to the material manufactured by the company, and so may be different from that obtained from the above mentioned publications. Often information regarding compliance with minimum requirements is also provided by the manufacturers.

However, judicious use of such data is important, as there are numerous protective clothing and chemical combinations. The data from the recommended list should not be a basis for selecting material for protection against chemicals not represented on the list or against a mixture of chemicals. To the extent

| Gaseous test chemicals | Class                  |
|------------------------|------------------------|
| Ammonia                | Strong base            |
| 1,3-Butadiene          | Olefin                 |
| Chlorine               | Inorganic gas          |
| Ethyl oxide            | Oxygen heterocyclic gas|
| Hydrogen chloride      | Acid gas               |
| Methyl chloride        | Chlorinated hydrocarbon|

| Liquid test chemicals  | Class                  |
|------------------------|------------------------|
| Acetone                | Ketone                 |
| Acetonitrile           | Nitrile                |
| Carbon disulfide       | Sulfur-containing organic|
| Dichloromethane        | Chlorinated hydrocarbon|
| Diethylamine           | Amine                  |
| Dimethylformamide      | Amide                  |
| Ethyl acetate          | Ester                  |
| n-Hexane               | Aliphatic hydrocarbon  |
| Methanol               | Alcohol                |
| Nitrobenzene           | Nitrogen-containing organic|
| Sodium hydroxide       | Inorganic base         |
| Sulfuric acid          | Inorganic acid         |
| Tetrachloroethylene    | Chlorinated hydrocarbon|
| Tetrahydrofuran        | Oxygen heterocyclic    |
| Toluene                | Aromatic hydrocarbon   |
possible, the selection of textile materials should be based on test data for the potential challenge. Materials manufactured to provide protection against specific chemical hazards require the use of challenge liquids that represent the potential risk. For example, a pharmacist working with drugs for chemotherapy needs protective clothing and accessories that protect the individual from those drugs. A garment that provides general protection against commonly used chemicals may not be recommended for this use. Special testing would have to be conducted for the proposed end use.

4.4.2 Biological protection performance

The selection of protective clothing that provides protection against biological hazards depends on the proposed end use of the clothing. Some of the common end uses are to protect the patient as well as medical professionals who are exposed to blood-borne and other pathogens. Until recently, the majority of biological hazard test methods and guidelines focused on applications in the medical field and for military personnel. With the current bio-terrorism threats, biological protection is important for ‘first responders’, workers with the potential of exposure to hazardous materials, and the general public. Biological hazards are commonly bacteria, viruses, or toxins that exist as very fine air or liquid-borne particles.

Given below are examples of ASTM International and ISO standards that illustrate the specificity of the garments.

- F1670-03 Standard Test Method for Resistance of Materials Used in Protective Clothing to Penetration by Synthetic Blood.
- F1671-03 Standard Test Method for Resistance of Materials Used in Protective Clothing to Penetration by Blood-Borne Pathogens Using Phi-X174 Bacteriophage Penetration as a Test System.
- F1819-04 Standard Test Method for Resistance of Materials Used in Protective Clothing to Penetration by Synthetic Blood Using a Mechanical Pressure Technique.
- F1862-00a Standard Test Method for Resistance of Medical Face Masks to Penetration by Synthetic Blood (Horizontal Projection of Fixed Volume at a Known Velocity).
- F2100-04 Standard Specification for Performance of Materials Used in Medical Face Masks.
- F2101-01 Standard Test Method for Evaluating the Bacterial Filtration Efficiency (BFE) of Medical Face Mask Materials, Using a Biological Aerosol of Staphylococcus aureus.
- F2299-03 Standard Test Method for Determining the Initial Efficiency of Materials Used in Medical Face Masks to Penetration by Particulates Using Latex Spheres.
4.4.3 Flame and thermal protection performance

The selection of protective clothing that provides protection against heat and burning objects depends on the proposed end use of the clothing. Some of the common applications are to protect individuals from open flames (including flash fires), molten materials, and radiant heat. In general, materials that have inherent flame-resistant properties are used for flame and thermal protection. Often thermal protective apparel requires the use of multi-layered fabric construction, with each layer performing a specific function. Thus performance is measured for individual layers as well as for the whole garment assembly. Protective apparel is worn by firefighters, wildland firefighters, electrical linesmen, racing- and rally-car drivers, emergency services personnel, and many other groups. Standards and performance specifications on selection, use, care and maintenance of flame and thermal clothing, including fabric, are available through national and international standardization bodies such as NFPA International, ISO, OSHA, and ASTM, CEN/TC 162 (European Technical Committee for Protective Clothing). Due to the very specific requirements, there are many specifications for protective clothing used for protection against thermal and flame hazards. Given below are examples of ASTM, EN, and NFPA standards that illustrate the specificity of the garments.

- F955-03 Standard Test Method for Evaluating Heat Transfer through Materials for Protective Clothing upon Contact with Molten Substances.
- F1002-96 Standard Performance Specification for Protective Clothing for Use by Workers Exposed to Specific Molten Substances and Related Thermal Hazards.
- F1060-01 Standard Test Method for Thermal Protective Performance of Materials for Protective Clothing for Hot Surface Contact.
- F1358-00 Standard Test Method for Effects of Flame Impingement on Materials Used in Protective Clothing Not Designated Primarily for Flame Resistance.
- F1930-00 Standard Test Method for Evaluation of Flame Resistant Clothing for Protection Against Flash Fire Simulations Using an Instrumented Manikin.
Steps in the selection of protective clothing materials

- F1939-99a Standard Test Method for Radiant Protective Performance of Flame Resistant Clothing Materials.
- NFPA 70E Standard for Electrical Safety Requirements for Employee Workplaces.
- NFPA 2113 Selection, Care, Use and Maintenance of Flame-Resistant Garments for Protection of Industrial Personnel against Flash Fire.
- NFPA 1971, Standard on Protective Ensemble for Structural Fire Fighting, 2000 edition.
- NFPA 1976, Standard on Protective Ensemble for Proximity Fire Fighting, 2000 edition.
- NFPA 1977, Standard on Protective Clothing and Equipment for Wildland Fire Fighting, 2000 edition.
- NFPA 1991, Standard on Vapor-Protective Ensembles for Hazardous Materials Emergencies, 2000 edition.
- NFPA 1992, Standard on Liquid Splash-Protective Ensembles and Clothing for Hazardous Materials Emergencies, 2000 edition.
- NFPA 1999, Standard on Protective Clothing for Emergency Medical Operations, 1997 edition.
- NFPA 2113, Standard on Selection, Care, Use, and Maintenance of Flame-Resistant Garments for Protection of Industrial Personnel Against Flash Fire, 2001 edition.
- EN 469: European standard for fire fighters’ personal protective equipment.
- EN 531: European standard for heat and flame protective clothing for industrial workers.
- EN 659: European standard for fire fighters’ gloves.
- ISO 17492:2003 Clothing for protection against heat and flame – Determination of heat transmission on exposure to both flame and radiant heat.
- ISO 2801:1998 Clothing for protection against heat and flame – General recommendations for selection, care and use of protective clothing.
- ISO 6942:2002 Protective clothing – Protection against heat and fire – Method of test: Evaluation of materials and material assemblies when exposed to a source of radiant heat.
- ISO 8194:1987 Radiation protection – Clothing for protection against radioactive contamination – Design, selection, testing and use.
- ISO 9150:1988 Protective clothing – Determination of behaviour of materials on impact of small splashes of molten metal.
- ISO 9151:1995 Protective clothing against heat and flame – Determination of heat transmission on exposure to flame.
- ISO 9185:1990 Protective clothing – Assessment of resistance of materials to molten metal splash.
- ISO 11612:1998 Clothing for protection against heat and flame – Test methods and performance requirements for heat-protective clothing.
4.4.4 Mechanical protection performance

Protective clothing designed to provide protection from mechanical hazards ranges from cut protection for chainsaw workers to body amour designed for bullet, stab, puncture, or impact protection for police and military personnel. Ballistics tests and performance standards, developed by the National Institute of Justice (NIJ), are examples of the specialized ballistic tests that are used to determine the performance of the materials (6). Numerous standards are available to measure the cut resistance of materials used to protect individuals from chainsaw cuts. Given below is a list of test standards and performance specifications developed by ASTM International for cut resistance.

- F1790-04 Standard Test Method for Measuring Cut Resistance of Materials Used in Protective Clothing.
- F1414-99 Standard Test Method for Measurement of Cut Resistance to Chain Saw in Lower Body (Legs) Protective Clothing.
- F1458-98 Standard Test Method for Measurement of Cut Resistance to Chain Saw of Foot Protective Devices.
- F1818-97(2003) Standard Specification for Foot Protection for Chain Saw Users.
- F1897-98 Standard Specification for Leg Protection for Chain Saw Users.
- F1342-91(1996)e2 Standard Test Method for Protective Clothing Material Resistance to Puncture.
- F1414-99 Standard Test Method for Measurement of Cut Resistance to Chain Saw in Lower Body (Legs) Protective Clothing.
Knowledge of how the fabric provides the protection as well as the limitations of the material is important. Materials may have similar barrier performance; however, the manner in which the protection is provided may vary considerably. One may provide protection due to the inherent fiber properties, whereas another from a finish applied to the fabric. It would be important to obtain additional information on the durability of the finish to determine the level of protection that will be provided over the life of the garment. The durability of the finish may be a limitation for the material.

The above discussion provides a sense of the level of complex analysis that must be applied for each type of hazard (chemical, biological, physical, radiological, or thermal).

After such an analysis, a list is prepared of materials that meet the minimum protection requirements. This list is then used to select potential materials based on other major factors discussed in the following section. Some manufacturers provide online interactive software to assist in the selection of suitable clothing. DuPont™ SafeSPEC™ is an example of an interactive tool that assists the user with hazard assessment and selection of apparel. As stated in the software, the responses are based on the information provided by the user. Thus, it is crucial for the individual entering the information to provide accurate information. With systems that are manufacturer specific, it is difficult to compare products from different manufacturers.
4.5 Selection of materials based on other major factors

For protective clothing, protection provided by the material is the primary factor in its selection. In addition, there are several other factors that have to be considered while selecting the materials. As with any other selection processes, the various factors have to be weighted in order to select the appropriate material. Impact of the use of PPE on job performance is an important factor to be considered. In addition, factors such as comfort, durability, maintenance, cost, and design considerations may apply. The major selection categories with applicable sub-categories are discussed below.

4.5.1 Job performance

Problems with dexterity, added weight and bulk of the PPE, and heat stress are examples of factors that may affect job performance. The type of burden the use of material will pose is dependent on the part of the body that is covered with the textile material as well as the type of job. For example, the weight of the protective gear may be a factor for firefighters fighting wildland fires; whereas, dexterity may be crucial for protective gloves worn by surgeons and other health professionals. Dexterity is an important factor while selecting glove materials for various end uses. Test standards have been developed to measure the dexterity of gloves. F2010-00 Standard Test Method for Evaluation of Glove Effects on Wearer Hand Dexterity Using a Modified Pegboard Test is an example of a test standard used to measure dexterity of the glove. The suitability of standards to assess dexterity of the material for a specific job should be considered carefully as the type of hand movements required to do the job may not be similar to those used in the standard.

In situations where the garment has to be worn on a regular basis for an extended period of time, bulk and weight often become major factors in the selection of protective clothing materials. The problem is compounded by the use of multiple layer clothing and additional equipment that has to be carried to perform the job. Protective clothing materials for military personnel and firefighters fighting wildland fires are examples of end uses where weight and bulk of protective clothing and equipment would be a factor in selection. Appropriate body armor worn by law enforcement personnel is an excellent example of an end use where bulk, weight, and flexibility of the body armor are very important to material selection. Given below is information on selection of body armor published as part of the body armor standard18 (see also Chapter 19 on ballistic protection):

Type I body armor, which was issued during the NIJ demonstration project, is the minimum level of protection that any officer should have, and is totally suitable for full-time wear. A number of departments desiring more than
minimum protection wear type II-A armor, which has been found sufficiently comfortable for full-time wear where the threat warrants it, particularly for those departments that use lower velocity 357 Magnum service weapons. Type II armor, heavier and more bulky than type II-A, is worn full time by some departments, but may not be considered suitable for full-time use in hot, humid climates. Type III-A armor, which provided the highest level of protection available as soft body armor, is generally considered to be unsuitable for routine wear, however, individuals confronted with a terrorist threat may be willing to tolerate the weight and bulk of such armor while on duty. Type III and IV armor are clearly intended for use only in tactical situations when the threat warrants such protection.

Job performance and comfort are closely related. Often discomfort affects the ability of the individual to perform his/her job efficiently and effectively. Comfort-related examples are included in the next section.

4.5.2 Comfort

In many cases the use of PPE may negatively impact the comfort of the user. Reduced comfort results in lower user compliance and potential for heat stress injuries. Environmental or climatic conditions as well as the type and level of activity are major factors that contribute to the potential for heat stress. Thus, adequate comfort is a primary concern in hot and humid climates, as well as in environments where the individual is exposed to a heat source. According to the guidelines published by NIOSH:

\[\ldots\text{the frequency of accidents, in general appears to be higher in hot environments than in more moderate environmental conditions. One reason is that working in a hot environment lowers the mental alertness and physical performance of an individual. Increased body temperature and physical discomfort promote irritability, anger, and other emotional states which sometimes cause workers to overlook safety procedures or to divert attention from hazardous tasks.}\]

To the extent possible, material should be carefully selected to balance the protection and comfort properties. In end uses where suitable protective clothing materials cannot provide the required protection and comfort, solutions such as the use of cooling devices, or use of work and rest cycles reduce the risk of heat stress. For example, cooling devices are used to reduce the potential for heat stress for firefighters. They are generally designed to provide the required comfort for a limited period of time. Willingness to use protective clothing materials that provide protection but are uncomfortable depends on factors such as awareness of risk and consequences for non-compliance. An individual may be willing to bear the discomfort in order to remain protected or comply with the requirements if he/she sees the benefit in wearing the protective clothing.
The measurement of comfort is very complex as many factors contribute to the comfort provided by a garment to an individual. A variety of tests are conducted to measure these properties. Material characteristics such as air permeability and moisture vapor transmission are used to quantify comfort characteristics. However, these do not take into consideration factors such as heat generated as a result of physical activity. Human subject studies that include physiological monitoring as well as self-reported questionnaires are also used to measure comfort. Factors such as perceived comfort, physical condition of the individuals, and duration of the test are some of the factors that affect the results of human subject studies. A newer method measures the micro-environment that is produced between the garment and the skin as an indicator of comfort. Thermal, sweating, and movable manikins are also being used to measure comfort.

4.5.3 Cost

Cost is often an important concern for the individuals procuring the garments. It is not unusual for the procurement department, especially government departments, to purchase PPE based on the cost, using competitive tendering processes. The type of garment plays a major role in determining the cost of the garment. For some end uses, limited use or reusable PPE may be selected. In these situations the added cost of cleaning, maintaining and disposing of PPE should be considered while selecting the materials. Often the initial cost of a limited use garment may be fairly low, but the added cost of purchasing new garments and disposal of the contaminated garments might outweigh the initial cost benefit. On the other hand, the cleaning cost of reusable garments may justify the use of limited-use garments.

4.5.4 Durability

Durability of the material determines the performance or the wear life of the garment. The extent to which durability is a concern is dependent on the proposed end use. The material should be able to withstand the normal wear and tear expected for the job that is being performed. Physical characteristics that are commonly measured and reported for protective clothing materials are tensile strength, tearing strength, bursting strength, abrasion resistance, puncture resistance, and cut resistance. In addition fabric weight, flexibility, flammability, and degradation due to environmental conditions may also be measured. Often the performance specifications include minimum requirements for limited use and reusable materials. For materials in which a finish is applied to provide protection, determination of the durability of the finish is very important. The protective properties and thus the wear life of these materials may be reduced.
4.5.5 Use, care, and maintenance

Intended use, decontamination, maintenance, storage, and disposal factors should be considered prior to selecting a material. The impact the material will have on the use, care, and maintenance of the garment needs to be considered. The compatibility of the various materials in the manufacture of multicomponent materials should also be considered.

4.5.6 Cultural factors

In addition to the above factors, selection of protective clothing materials may be affected by cultural factors, especially for comparatively lower risk applications. Thus, it is difficult to develop protective clothing materials that are accepted globally. It is also important for the individual responsible for making decisions to have an understanding of the culture. Decisions made by individuals solely on performance specifications have resulted in non-compliance due to low user acceptance of the recommended PPE for cultural reasons. User acceptance of protective clothing worn by pesticide applicators is used as an example of how factors such as color and materials can be important in the selection of protective clothing. A report published on the Safe Use project in Kenya explains:\(^{20}\)

> Persuading farmers to use protective clothing was one of the biggest challenges. They see it as uncomfortable and expensive. Locally designed and manufactured clothing is addressing these problems. More specifically, women in Africa have a cultural aversion to being seen in trousers. Kenyan women were therefore asked to design their own protective clothing and the results have been widely publicised.

4.6 Future trends

The current trend of standards organizations focusing on the development of performance based specifications will continue. Comprehensive specifications will include information on selection, use, care, and maintenance (SUCM). The development of these specifications will assist in the selection of appropriate protective clothing materials. The need to protect individuals from multiple hazards such as chemical, biological, and thermal will require streamlining of the selection process. The use of online systems, databases, and knowledge bases will continue to expand. In the future online systems pertaining to protective clothing will, in all probability, include global mega-knowledge bases with built-in information on compliance requirements. Selection of protective clothing materials based on performance based specifications will be an integral part of the system. In building these systems, it will be important to ensure that the system is used to assist but not replace the decision makers. The individual
selecting the materials(s) should be involved with each step of the selection process. An online system entitled ‘Work and Protective Clothing for Agricultural Workers’ is being used as an example to illustrate the use of databases and the Internet as tools for the selection of protective clothing materials. A brief description of this system is included in section 4.6.1.

4.6.1 Sample online system

The system provides a structured systematic process for data collection, analysis, and dissemination. Online data entry forms are used to enter the raw data and material information. The raw data is used to calculate the values in accordance with applicable standards. These are stored for access through easy to use dropdown menus.

4.6.2 Data entry and calculations

The first step in the data entry process is the auto generation of a fabric code based on information regarding fiber content, country, and fabric construction (Fig. 4.2). The next step is entry of information regarding type of garment, cost, source, etc. (Fig. 4.3). Then the fabric is tested and the raw data entered by the operator using online forms. The hard copies of the raw data are retained for verification. The system uses the raw data to calculate results such as mean and standard deviation. These results are stored in a table for later use.

4.6.3 Statistical model

Data from over sixty fabrics in the database was used to develop a statistical model to predict percent pesticide penetration through the material. Data was analyzed to identify the key factors that affect pesticide penetration. Currently

4.2 Screen to auto generate fabric codes (Source: Work and Protective Clothing for Agricultural Workers, University of Maryland Eastern Shore).
the scope of the statistical model is limited to estimating pesticide penetration of three formulations through woven fabrics (Fig. 4.4).

4.6.4 Data dissemination

Easy to use dropdown menus are used to disseminate textile material and penetration data sorted into various categories (Fig. 4.5). Individuals can also use the system to customize their search by defining the search criteria (Fig. 4.6). Once performance specifications have been established, individuals will be able to select materials that meet the performance specifications.
4.6.5 Suggestions model for future systems

The flowchart that outlines the steps involved in the selection process is given in Fig. 4.7. The work scenario(s) and hazard(s) will be entered by the user through the online input screen. Based on the information entered, the system will list relevant standards. If relevant standards are available, the user will select the
4.7 Recommended steps in the selection of textiles for protective clothing.

**Assess hazard**
- type of hazard(s)
- level of exposure
- duration of exposure
- severity of the hazard

**Identify relevant standards**
- regulatory standards
- guidelines
- test standards

**Relevant standards**
- Yes
- No

**Identify tests required to determine the performance**

**Conduct test/fill voids**

**Compile a list of fabrics that meet requirements**

**Use other factors to select fabrics**
- job performance
- comfort
- cost
- durability
- use, care, and maintenance
- cultural factors

**Fabrics meet all requirements**
- Yes
- No

**Select fabric**
standard and proceed to the next step. If no relevant standards are available, the user will have the option to use the system to select the test methods, and/or enter data, and then move to the next step (see Fig. 4.7). In the next step, the user will enter the information regarding other factors such as durability, cost, etc., that are important in the decision making process. This information will be used to identify the fabrics that meet all requirements. If fabrics meet the requirements, final selection will be made. If fabrics do not meet all requirements, the requirements will have to be adjusted prior to final selection.

4.7 Sources of further information and advice

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4. CEN – European Committee for Standardization, Central Secretariat, rue de Strassart 36, B-1050 Brussels, Belgium.
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6. Technology Assessment Program, National Institute of Justice, U.S. Department of Justice, Washington, DC 20531. Publications available through National Criminal Justice Reference Service.
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