A REVIEW of GAPS and LIMITATIONS in TEST METHODS FOR FIRST RESPONDER PROTECTIVE CLOTHING and EQUIPMENT

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EXECUTIVE SUMMARY

This report presents the results of a review aimed at identifying test methods for protective clothing for first responders, as well as identifying areas in which further research is required. It is intended to identify gaps and limitations in evaluation technology and to provide information on test methods research that can guide the development of new first responder protective ensembles.

This project reviewed test methods specified by the National Fire Protection Association (NFPA) comprehensive standards for structural firefighters, HAZMAT response, Emergency Medical Service (EMS), technical rescue operations, response to chemical/ biological terrorism incidents and standards for selection care and maintenance of firefighting protective ensembles. Key test methods and requirements for evaluating protective clothing and equipment in the performance categories of flame and heat protection, chemical protection, biological protection, physical hazard protection, and for testing and evaluating heat stress are referenced. In addition, this project surveyed documented research on test methods for firefighter and other emergency responders.

Available testing technologies and performance requirements were evaluated based on the following general criteria:

- Tests and performance requirements should provide reasonable simulation of emergency responder multi-threat environments.
- Test methods and criteria should enable ensemble development based on competing performance needs - protection, functionality and comfort.
- Test methods should provide information on ensemble performance, in addition to data on materials and components.
- Translation from bench top laboratory tests of material properties to ensemble and field performance should be scientifically qualified for the conditions of emergency response.

Based on these assessment criteria, the following needs for test method development have been identified:

- Whole garment tests and performance criteria for protection and heat stress.
- Simulant tests for chemical/ biological threats.
- Tests for biological threats from aerosols and/ or particulates.
- Simulant tests for toxic agents for SCBA gear (NIOSH approval criteria).

- Tests for thermal protection in sub-flashover environments.
- Tests for the ergonomic function and comfort of ensembles and components.
- Tests for the ruggedness of ensembles for technical rescue.
- Tests for the service life of ensembles and components.
- Ensemble design tools based on predictive models of protective performance and heat stress.

The availability of these testing procedures and performance criteria would greatly contribute to the development and evaluation of new protective ensemble technologies. They would also provide for improved performance standards for protective clothing and equipment used in emergency response.

CHAPTER I

Test Methods and Criteria for Emergency Responder Protective Clothing and Equipment

Firefighters and other emergency responders need protection from a wide range of threats. Firefighters need protection against the traditional hazards of radiant and conductive thermal exposure, unexpected flashover conditions, toxic smoke, puncture and abrasion. Emergency responders face increasing risk of chemical and biological exposure due to terrorism, along with the ongoing potential for exposure to toxic industrial chemicals and materials. The development of advanced protective ensembles and equipment for emergency responders requires a systematic basis for testing and evaluating the ability of personal protective systems to protect responders in multi-threat environments, while also providing adequate levels of dexterity and sustainable functionality.

Background

Considerable research has been devoted to the development of test methods for evaluating protective clothing and equipment used by emergency responders. In addition, the National Fire Protection Association (NFPA) has developed comprehensive standards for fire service protective clothing and equipment. As a result of the gaps assessment conducted by this project, the following areas have been identified as being important to future test methods needs:

- Development of new or improved tests of thermal protective performance for garments and ensembles.
- Development of new or modified procedures for evaluating protection against chemical and biological hazards.
- Development of tests for heat stress, ergonomics and physiological issues associated with the performance of protective ensembles.
- Development of tests for physical hazards and for predicting the in-use durability and service life of protective components and systems.
- Development of computer based models to predict the protective performance and heat stress of protective ensembles.

Testing requirements for first responder protective clothing and equipment necessarily depend on the intended mission and the performance needs of the mission. This report will concentrate on assessing gaps in testing technologies relevant to specific areas of emergency response including structural firefighting, HAZMAT response, Emergency Medical Service (EMS), technical operations and response to Weapons of Mass Destruction (WMD).

Gaps and Limitations in Evaluation Technologies

This project reviewed test methods and performance criteria specified by the National Fire Protection Association including:

- NFPA 1971 Standard on Protective Ensemble for Structural Fire Fighting, 2000 Edition [107].
- NFPA 1994 Standard on Protective Ensembles for Chemical/ Biological Terrorism Incidents, 2001 Edition [106].
- NFPA 1991 Standard on Vapor-Protective Ensembles for Hazardous Materials Emergencies, 2000 Edition [108].
- NFPA 1992 Standard on Liquid Splash Protective Ensembles and Clothing for Hazardous Materials Emergencies, 2000 Edition [109].
- NFPA 1951 Standard on Protective Ensembles for USAR Operations, 2001 Edition [104].
- NFPA 1999 Standard on Protective Clothing for Emergency Medical Operations, 2003 Edition [102].
- NFPA 1851 Standard on Selection, Care, and Maintenance of Structural Fire Fighting Protective Ensembles, 2001 Edition [105].

Many of these standards, including NFPA 1951, NFPA 1991, NFPA 1994, and NFPA 1999, have been adopted by the U.S. Department of Homeland Security through its Science and Technology Division, and by the Inter-Agency Board for Equipment Standardization and Interoperability (IAB), as listed in the organization's 2002 Annual Report [74].

A summary of key test methods and requirements for evaluating protective clothing and equipment in the performance categories of flame and heat protection, chemical protection, biological protection, physical hazard protection, and for testing and evaluating heat stress is provided in report Appendix A. Based on a review of these methods, the gaps and limitations in available evaluation technologies can be summarized as follows:

1. Whole Garment Tests and Performance Criteria for Protective Ensembles

A key factor determining the performance of protective clothing and equipment for emergency operations is balancing protection against a multitude of different hazards while providing necessary comfort and functional performance. Protective garments for first responders must provide thermal protection and chemical/ biological protection while providing for sustained use. Test methods and performance criteria aimed at simultaneously maximizing all three competing performance areas are needed. Current standards rely almost exclusively on bench top test methods to assess swatch size materials or components of protective clothing and equipment. This approach fails to take into account design issues that have a significant impact on wearer acceptability. Advanced instrumented manikin tests for comfort (sweating manikin), thermal protection (thermal manikin), and aerosol/ liquids penetration can be applied to full ensembles. These tests can then be combined with controlled human physiological stress and comfort/ ergonomic evaluations to validate the measurements and provide the needed improvements for ensemble designs and material selection.

2. Simulant Tests for Chemical/ Biological Agents

A key area of interest in chemical/ biological protection is resistance to inward leakage of gaseous, vapor, and liquid toxic agents through respirators and clothing. Field use of protective ensembles demands resistance to longer-term exposure to these threats, as well as to industrial chemicals, to maintain strength and durability. Use of potent toxic agents to perform the required barrier testing has a number of drawbacks. Access to the agents and expense of such testing serves as a significant barrier to development of improved designs and materials. The toxicity of the exposed ensembles eliminates the *post hoc* testing and analysis by the developer. The latter situation makes the tests essentially pass/ fail situations and prevents analysis of mechanisms of failure - a critical part of making improvements in materials and designs. The expense and availability of testing with toxic agents, particularly when required for several parts of the ensemble (respirator, garment, visor, glove, and footwear materials in addition to seams), discourages manufacturer certification of products. Therefore, appropriate, low toxicity simulants are critically needed to replace highly toxic agents so as to facilitate product improvement, standards development, and certification.

3. Tests for Biological Threats from Aerosols and/ or Particulates

The potential for exposure of first responders to biological threats from aerosols and/ or particulate dispersions has long been recognized. Widespread respiratory damage to search and rescue teams and cleanup crews after the 9/11 terrorist incident, and the illnesses and deaths from anthrax exposures via exposure to inhalation from mailed powders, provided powerful insights to the potential seriousness of this threat. The response community has little direction and virtually no information about the appropriateness of different clothing outfits for this type of response, especially given the repeated need for such responses. Whole clothing assessment techniques are needed that can be applied to clothing that can protect the wearer from exposure to airborne bioterrorism particulates using stimulant substances under controlled circumstances.

4. Simulant Tests for Toxic Agents for SCBA Gear (NIOSH Approval Criteria)

Inward leakage of gaseous, vapor, and liquid contaminants through respirators and interfaces with the body and garments are a potential catastrophic risk for the first responder. With the recent development of performance criteria for self-contained breathing apparatus (SCBA) against chemical agents, concerns have arisen regarding the difficulty and expense in using toxic chemical agents, and regarding the ability to analyze items that have been tested. SCBA equipment cannot be properly analyzed for the effects of exposure due to the residual potent toxins that may be present. The expense and accessibility of toxic exposure testing also discourages manufacturer certification of products.

5. Tests for Thermal Protection in Sub-Flashover Environments

Firefighters can receive burns while working in thermal exposures that are considerably less intense than flashover conditions. Such exposures last several minutes, and are not intense enough to degrade the outer shell of the protective ensemble. These phenomena are thought to be associated with the discharge of thermal energy stored in the protective suit materials, in addition to transmitted radiant energy. While test methods are available for measuring the thermal protective performance of materials in flashover conditions, no optimized laboratory test method is currently available for evaluating the thermal protective performance in prolonged exposures to low level radiant heat, or for assessing the effect of absorbed moisture on burn protection in these conditions.

6. Tests for Ergonomic Function and Comfort

Bulky and restrictive protective clothing can encumber dexterity and limit effective emergency response. In addition, wear comfort and ergonomic functions have been largely overlooked in testing standards for protective clothing. Reliable laboratory test methods are needed to measure material properties associated with sensorial comfort and dexterity, including tests for sweat absorption, material stiffness and friction. Guidelines for ergonomic/ comfort testing of first responder gear need to be developed to assess new ensemble designs.

7. Tests for Ruggedness of USAR Ensembles

As identified in emergency response events related to the September 11 attacks, first responders found that their clothing, gloves, and footwear, quickly deteriorated with the long-term rescue efforts associated with these events. Even though intended for structural fire fighting, both gloves and footwear quickly deteriorated and required frequent replacement. Improved laboratory tests are needed to reliably predict protection from cuts, abrasion and puncture in extended use. These performance requirements for physical protection and durability testing need to be addressed with focused research efforts.

8. Tests for In-Use Durability and Service Life

The development of advanced ensembles for emergency responders requires protocols for testing and verifying that these systems provide primary protection against invasive threats, while maintaining adequate levels of functional performance. Comparatively little research has been conducted in this area, probably because of the multitude of ensemble and exposure conditions that combine to degrade the performance of emergency gear. Emergency responders may expose protective clothing and equipment to heat, chemicals, soiling, UV radiation, abrasion and compression, and saturation with sweat and water. Test methods and performance criteria are needed to evaluate and predict the effect of these conditions on thermal, chemical/ biological resistance and comfort.

9. Computer Based Predictive Models

The utility of data generated by laboratory tests would be greatly increased by the availability of computer based models that can analyze and interpret results in the light of material properties and garment design. The analytical models could serve as tools to assist the development of new materials. They could also forecast the effects of design options on the resulting protection and comfort on ensembles for emergency response. Development of performance predicting models will require significant advances in our present understanding of heat and mass transfer processes in protective clothing systems and how these processes influence thermal and chemical/ biological protection.

Research Projects for Test Methods Development

These identified gaps and limitations in available methodologies and performance criteria provide specific basis for research projects for test methods development. State-of-the-art testing approaches and research needs are discussed in the following chapters of this report.

CHAPTER II

THERMAL PROTECTIVE PERFORMANCE

Although firefighters face multiple threats, protection from thermal hazards is of primary concern. Laboratory test methods for measuring the thermal protective performance of firefighter protective clothing and equipment should simulate, as accurately as possible, the heat hazards present at the fire scene.

Firefighter Thermal Environments

In order to select appropriate thermal exposures for testing purposes, the conditions under which firefighter protective clothing will be used must be considered. However, it is quite difficult to completely define the firefighter environment. This is because of the many environmental, physical, physiological and psychological factors that affect a firefighter's interaction with the fire scene. Nonetheless, data has been collected and information is available to provide a range of common thermal environmental conditions that are classified into three general categories. These classifications are identified as routine, hazardous, and emergency, and are summarized in Table 1 and discussed below.

Table 1. Firefighters' Thermal Environments.

Exposure	Air Temperature (°F/ °C)	Radiant Flux ($cal/cm^2 \cdot sec$)	Tolerance Time
Foster & Roberts [50]			
Routine	100°C	0.02	25 minutes
Hazardous	120°C	0.07	10 minutes
	160°C	0.10	1 minute
Emergency	160 - 235°C	0.23	< 1 minute
Abbott [2]			
Routine	20 - 70°C	< 0.04	10 - 20 minutes
Hazardous	70 - 300°C	0.04 - 0.30	1 - 5 minutes
Emergency	300 - 1200°C	0.30 - 5.0	15 - 20 seconds
Coletta [33]			
Routine	140°F (60°C)	0.03	5 - 60 minutes
Hazardous	572°F (300°C)	0.20	5 - 20 minutes
Emergency	1832°F (1000°C)	2.50	5 - 20 seconds

Routine Conditions: These conditions are applicable to firefighters who are operating hoses or otherwise fighting fires from a distance, where no special clothing is necessary. According to Foster et. al. [50], the limits proposed are 25 minutes at 100°C and a thermal radiation limit of 0.024 cal/cm^{2}sec (1kW/m^2). Abbott et. al. [2] associates conditional limits of 20 - 70°C with thermal radiation of < 0.04 cal/cm^{2}sec (1.67kW/m^2).

Hazardous Conditions: These conditions (described as "ordinary" by Abbott et al.) are typical of those that would be encountered outside a burning room or small burning building. According to Hoschke [71], the lower bounds of this region are similar to firefighters ventilating a fire without water support, while the upper limits are applicable to those who are first into a burning building. Nonetheless, a "turnout" uniform is necessary to provide burn protection and to minimize thermal stress the firefighter may encounter. The range set by Foster et. al. [50] has been taken to be at least 1 minute at 160 °C and a thermal radiation of 0.096 cal/cm^{2}sec (4kW/m^2) and can be tolerated up to 10 minutes. Abbott et al. [2] describe this condition as lasting 10 - 20 minutes with air temperatures of 70°C - 300°C with thermal radiation of 0.04 cal/cm^{2}sec to 0.30 cal/cm^{2}sec (4.0 to 12.56 kW/m^2).

Emergency Conditions: These conditions may be encountered during "flashover" of a large building fire. These conditions have been taken to be above the range of "Hazardous" conditions and ranging to beyond 235°C and 0.23 cal/cm^{2}sec (10 kW/m^2) by Foster et.al. [50]. Severe thermal problems and life threatening injuries are associated with these conditions. Abbott et.al. describe these conditions as having temperatures of 300°C to 1200°C and 0.30 cal/cm^{2}sec to 5.0 cal/cm^{2}sec (12.56 to 209.34 kW/m^2).

The ultimate evaluation of the protective properties of a material or ensemble is its performance in actual end use or field conditions. This type of evaluation is only possible in very restricted use conditions and where hazardous exposures and injuries to first responders are not involved. Thermal protective clothing must perform over a wide range of exposure conditions and burn injury may occur even with very effective protection performance. The most important consideration is that the effects of the thermal exposure on protective performance must be replicated as accurately as possible with the instrumented test method. This situation calls for using exposure conditions that represent the actual thermal hazard.

Tests for Thermal Protective Performance (TPP)

TPP tests are the most important class of laboratory testing technologies used to evaluate the thermal protective performance of firefighter ensembles. This category of tests includes testing methodologies ranging from bench-scale tests of thermal protective insulation to full scale instrumented manikin assessment of whole garments exposed to simulated flashover conditions. This review has identified the following areas where gaps and limitations in TPP test methods need to be addressed:

- Development or adaptation of improved thermal sensors and associated skin burn translation models for TPP testing.

- Development of laboratory test methods and performance criteria for evaluating the potential for stored thermal energy and steam burn injuries associated with moisture accumulation in turnout suits.

- Development of a test method to measure the ability of firefighter turnout shell materials to retain strengths in exposure to flash fire conditions.

- Development of advanced articulated instrumented manikins for evaluating the protection of protective ensembles exposed to range of different thermal environments in realistic configurations and body postures.

These gaps and limitations will be discussed in light of the currently available test methods and needs for research to develop new testing technologies.

TPP Test for Emergency Conditions

Emergency fire threats are characterized by high intensity, short duration exposures of potentially immediate lethality. As indicated in Table 1, emergency fire environments can include flashover conditions that produce heat flux in the range of 0.3 to more than 5.0 cal/cm^{2}sec. Tolerance time for firefighters in these intense exposures is measured in seconds. In these exposures, the role of the protective gear is to provide insulation against transmission of injurious levels of heat to the skin for a time sufficient to allow the firefighter to escape the flashover environment.

The TPP test, required by NFPA 1971, measures the thermal protective insulation of firefighter turnout composites exposed to a bench-scale laboratory simulation of an emergency level fire exposure. A thermal protective performance tester is used to predict time to theoretical second-degree burn through fabric ensembles exposed to a 2.0 cal/cm^{2}sec (84KW/m^2) combined radiant convective heat source.

Figure 1. Thermal Protective Performance Tester.

The TPP test uses two laboratory burners and a radiant heat source provided by a bank of quartz tubes to deliver the exposure. Samples (6 inch x 6 inch) are exposed by moving the samples into position and opening a protective shutter. The heat transferred through the test material is measured by an instrumented copper calorimeter. The calorimeter consists of an 18g copper disk 40 mm in diameter and 1.6 mm thick with thermocouples positioned on a circle at half the radius of the disc, 120 degrees apart and one in the middle. The copper disk is painted dull black and mounted on an insulating board. The rate of temperature rise is used in conjunction with the calorimeter constants to complete the heat flux received. The test is conducted with the thermal sensor in contact with the thermal liner side of the turnout composite sample. The thermal protective performance of the test material is determined by comparing the measured heat transfer to the tolerance time of human tissue to a thermal assault as predicted by the Stoll model [136]. The tolerance time for a second-degree burn to occur is determined from the sensor response curve by comparing the calorimeter trace with the human tissue tolerance to heat obtained by integration of Stoll's curve with respect to time.

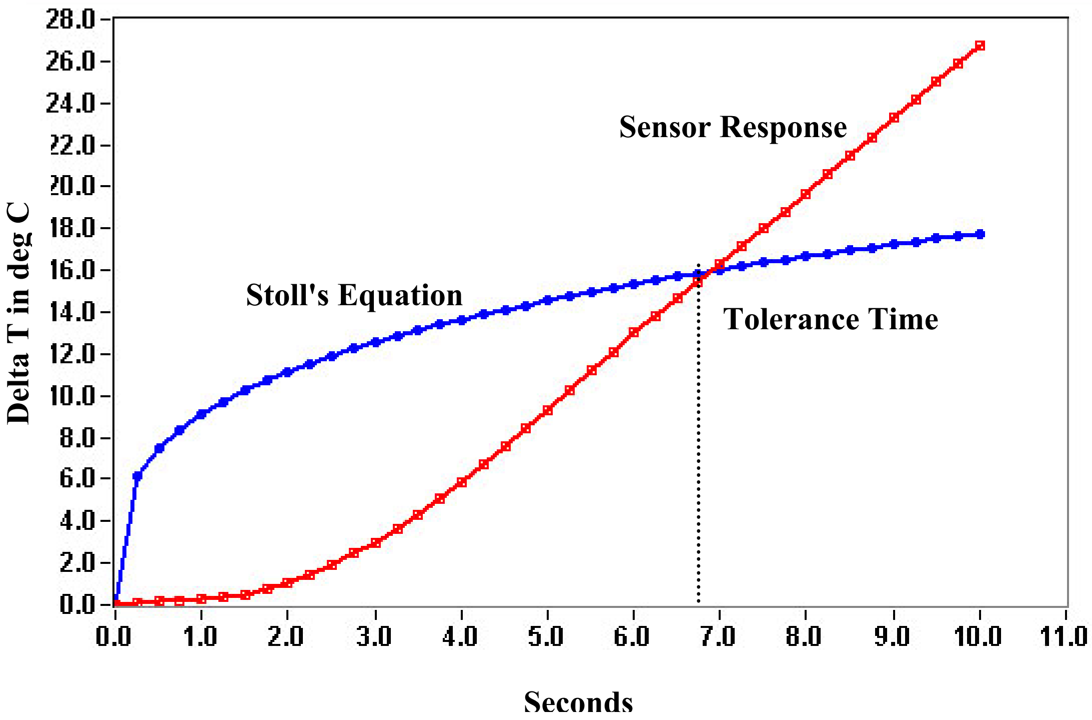


Figure 2. Illustration of Stoll Curve.

The TPP rating is defined as the total exposure energy, which causes the turnout composite to transfer a sufficient amount of heat to cause a second-degree burn injury (blister), and is calculated as:

TPP rating (cal/cm^2) = Tolerance time (sec) x Incident Heat Flux (cal/cm^{2}sec)

The NFPA 1971 standard requires turnout composites to have a minimum TPP rating of 35 cal/cm^2.

In addition to the TPP test, other bench scale test methods are commonly used to evaluate the thermal protective performance of protective materials. These tests include tests of radiant protective performance (RPP) resulting from contact with a hot surface [7]. NFPA 1971 calls for evaluating the effects of compression on heat transfer in materials used in the sholder and knee areas of fire fighter turnouts using a Conductive and Compressive Heat Resistance (CCHR) test [107]. Specimens are tested for both wet and dry conditions. The use of ASTM Test Method F1060 and ASTM F1939 to compare the thermal insulative performance of reinforced knee areas of firefighter protective clothing in hot surface contact and radiant exposures is discussed in reference [143]. In another study, a dynamic compression test apparatus was used to measure the thermal performance of knee pad systems when exposed to wet and dry thermal conditions [86].

TPP Tests for Sub-Flashover Conditions

Firefighters can receive burns in thermal exposures that are considerably lower than flashover conditions. These burns occur as a result of prolonged exposure in thermal environments classified as routine, or hazardous, in heat flux less than about 0.3 cal/cm^{2}sec (Table 1). These exposures are usually several minutes in duration, and the exposure levels are generally not sufficient to degrade the turnout shell fabric. Burns are thought to occur as a result of thermal energy transmitted to the garment through both radiant and convective source. Subsequent compression of the heated ensemble onto the body due to firefighter movement or external pressure can cause severe burns due to the discharge of stored thermal energy.

No standardized laboratory test method currently exists for evaluating the thermal protective performance of firefighter clothing with regard to the discharge of the stored thermal energy accumulated in sub-flashover environments. However, heat stored in firefighter turnout materials has been studied and a basis has been developed for bench-top stored energy tests [12-14]. These tests simulate a firefighter suddenly compressing the heated thermal protective turnout system against the body. Such compressions can be common due to repetitive flexion of limbs or due to compression of the turnout suit against hot fixed surfaces encountered in the firefighting environment. Output includes estimates of the time required for a firefighter under these conditions to receive a second-degree burn.

Technical advances are needed to develop test methods for evaluating thermal protective performance in prolonged exposures to radiant heat. Test methods for these conditions will benefit through the development of new radiant heat sources, as well as improved thermal sensors and burn translation algorithms. The thermal sensor used in the TPP test is a slug type sensor. The accuracy of heat flux measurements made with slug type thermal sensors decreases in prolonged heat exposures. At the same time, the widely used Stoll criterion for predicting second-degree burn injury is limited to short exposure times. Recent studies have shown the advantages that can be realized by employing new thermal sensor technologies and more sophisticated skin burn algorithms for estimating the thermal protective performance of protective clothing [15, 39, 58, 60]. Additional research is needed to comparatively evaluate thermal sensors and provide a detailed quantification of performance. Research is also needed to develop radiant heat sources that are capable of steady and accurate production of low-level heat flux (<0.5 cal/cm^{2}sec).

Measuring the Effects of Moisture on Thermal Protective Performance

Measurement of stored energy burn phenomena can be confounded by the presence of moisture in protective garments. This is an important consideration since firefighters often work in water-spray environments or kneel and crawl through puddles that render the outer side of the turnout suit saturated with water. Heat and heavy workloads cause the firefighter to perspire heavily, creating internal moisture loads. Accumulated moisture influences both the garment's heat conduction and its capacity to store thermal energy. Mechanisms controlling stored energy burns and so called "steam burns" are not yet well understood. NFPA and the firefighting community have recognized the need to understand the phenomena leading to moisture-related burns and to develop practical solutions for this problem.

Because moisture, present in protective clothing systems, has a complex influence on heat transmission and potential for skin burn injuries, there is significant interest in developing laboratory thermal protective performance testing protocols that incorporate reliable and realistic moisture preconditioning procedures. A major obstacle in the development of such testing methodologies is the lack of basic understanding of how moisture is absorbed in turnout systems when exposed, either to perspiration from a sweating firefighter, or to water from a fire ground source and how absorbed moisture effects thermal protection [12-14, 17, 78, 94, 110, 118, 119].

Research is needed to develop an understanding of how turnout systems absorb moisture from perspiration in wear and from laboratory devices that simulate perspiration from firefighters. Research is also needed to develop laboratory test methods for evaluating the effects of moisture on the thermal protective performance of firefighter protective clothing in sub-flashover conditions.

Instrumented Manikin Fire Tests

Results obtained from TPP tests are dependent on the mounting conditions for the turnout clothing swatches and do not always realistically mirror actual "wear and fit" spatial relations. Modern firefighting gear derives thermal protection not only from the characteristics of a single garment but by interactions between protective garments and equipment. For instance, thermal protection to the upper back is a function of shirt, protective overcoat, collar position (up or down), SCBA, and helmet [120]. To test any single item without the others present is a serious limitation of TPP tests. The results of manikin testing under flash fire conditions represent a significant step forward toward the evaluation of protective clothing and equipment.

Instrumented manikin technology has evolved to a level that permits assessment of the thermal protective performance of protective ensembles in realistic simulations of thermal exposures. The PyroMan Thermal Protective Clothing Analysis System is an example of state-of-the-art manikin fire test systems [35, 37, 112].

The PyroMan Thermal Protective Clothing Analysis System consists of an adult size male manikin (size 40 regular) made of high temperature flame-resistant polyester, fitted with 122 heat sensors distributed uniformly over the body (front and back), but not including hands or feet (Figure 3). Each sensor represents 0.82% of body area. Eight (8) large industrial propane gas torches carefully positioned and modified to create a controlled volume of fire that fully engulfs the manikin produce a computer controlled flash fire for testing firefighter turnouts, the heat flux level is typically set at 2.0 cal/cm^{2}sec. for a 10-second burn. The instrumented manikin and flame system is housed in a flame resistant chamber equipped with an exhaust system to rapidly remove products of combustion and degradation after every test exposure. Each of the 122 heat sensors consist of a thermocouple embedded below the surface of an epoxy-molded cone, which measures temperature at known depth. Sensors are individually calibrated to ensure accurate reading of temperature and calculation of surface heat flux. A computerized data acquisition unit scans and records each sensor's temperature every 0.5 second. The temperature readings, in conjunction with a one-dimensional transient heat conduction model, are used to compute the heat flux experienced at the sensor's surface as a function of time. The PyroMan system predicts burn injury by using Henrique's model to translate temperature readings into human tissue damage. The calculated heat flux is used together with estimates of human tissue physical properties and estimates of human tissue tolerance to intense heat to predict burn injury [68]. A thermal protective performance report is generated that includes the individual heat sensor responses, total accumulated heat

Figure 3. PyroMan Thermal Protective Clothing Analysis System

received by the heat sensors (cal/cm^2), percentage of manikin body receiving second-degree burn, percentage receiving third-degree burn, and a diagram showing burn intensity distribution over the entire manikin surface.

Standardized procedures for instrumented manikin fire tests of protective clothing are available through ASTM standards [8]. However, these testing procedures have not been specifically optimized for use in testing firefighter, and other emergency ensembles. Optimization of these methods for firefighters first responder ensembles will require further specification of ensemble configurations and test conditions including assessing the effects of SCBA cylinders and harness. It will also require advances in the basic technology of the instrumented manikins used in these tests [119].

The potential limitation of current instrumented manikins is that the technology cannot be used to evaluate all possible thermal exposures that commonly occur during the time that firefighters are making an emergency response:

- Instrumented manikins can only be positioned upright while firefighters are taught to remain as low down as possible. Different positions might affect both the location and intensity of thermal exposure.

- Instrumented manikins cannot be subjected to thermal stress imposed by repetitive compressions. For the torso and upper extremities, field condition scenarios do not realistically include repetitive compressions. For the knee and shin, repetitive compressions against the anterior surface do occur when firefighters crawl through the fire scene and/or operate hoselines. Under this scenario, compression testing for the anterior knee and shin areas might yield additional information incorporating articulation to evaluate burn exposure in the kneeling low-level position typically used for firefighting.

- Instrumented manikins cannot be subjected to prolonged moderate intensity thermal exposures. Transmission of heat in prolonged exposure to low-level heat is a potential source of firefighter burn injury.

- The impact of varying degrees of garment wetness on thermal protective performance cannot be addressed. Firefighters operate in clothing that rapidly becomes moist or wet from sweat (inside layers) and hose line water (outer layers). Added information would be gained from conducting test under varying conditions of turnout wetness.

- Developing a manikin system with thermal sensors located in the hands and feet, with additional sensors located in the manikin head, would permit evaluation of full protective ensembles including helmets, gloves, and footwear.

Research is needed to develop manikin testing procedures that are specifically designed to address the performance requirements of protective clothing and equipment for firefighters and other emergency responders.

Research Needs

Laboratory test methods for evaluating thermal protective performance run the gamut from bench top tests on fabric swatches to full-scale assessment of garment performance using an instrumented manikin. Each approach has its advantages and disadvantages with regard to the information provided and practical considerations involved in the implementation of the testing procedure. This review has identified the following specific areas where research is needed:

Ensemble Tests for Thermal Protection

The emphasis for firefighting clothing is focused on material performance. This approach fails to consider garment design features as they impact thermal protection. Bench-scale testing methods measure material characteristics, but are not able to address ensemble design and fit issues. Manikin testing of full ensembles will provide better laboratory prediction of garment field performance and address the effects of design features, which currently are not evaluated. Correlation of existing bench-level TPP tests results with more representative full ensemble testing is needed to provide the basis for performance standards that better represent the performance of actual turnout clothing ensembles in realistic exposures to thermal hazards.

Full ensemble test procedures and articulated instrumented manikins need to be developed to evaluate protective ensembles exposed to a range of different thermal events in realistic firefighting configurations and body postures.

Bench-scale Tests for Thermal Protection in Sub-Flashover Environments

Firefighters can receive burns while working in thermal exposures that are considerably less intense than flashover conditions. Such exposures usually last several minutes, and are not intense enough to degrade the outer shell of the protective ensemble. These phenomena are thought to be associated with the discharge of thermal energy stored in the protective suit materials, in addition to transmitted radiant energy. While test methods are available for measuring the thermal protective performance of materials in flashover conditions, no optimized laboratory test method is currently available for evaluating Thermal Protective Performance (TPP) in prolonged exposures to low level radiant heat, or for assessing the effect of absorbed moisture on burn protection in these conditions.

Research is needed to develop or adapt laboratory test methods and performance criteria for evaluating the thermal protective performance of firefighter clothing, including moisture effects, in sub-flashover heat exposures. Test method development may require the development of new bench scale radiant heat sensors and developing or adapting new thermal sensors and assorted algorithms for burns in prolonged exposures to sub flashover level heat.

Test methods developed through research in these areas will provide the basis for optimizing material design, garment design, and operational practices that will alleviate burns as a source of injuries to firefighters and other emergency responders.

CHAPTER III

CHEMICAL AND BIOLOGICAL PROTECTION

Firefighters and other first responders routinely encounter a variety of chemical and biological contaminants during emergency activities:

- Many structural fires involve bulk hazardous liquids at the fire scene with a range of different combustion products.
- Transportation accidents may yield contact spilled solid, liquid and gaseous hazardous substances.
- Victim rescue and provision of medical aid can result in exposure to potentially infected blood and body fluids.

In addition to ordinary hazards, firefighters must now face the potential for domestic terrorism involving chemical or biologically based weapons of mass destruction (WMD).

While specialized clothing is often considered the most appropriate approach for personal protection in instances involving chemical or biological hazards, statistics bear out that the ordinary firefighter is reliant on his structural fire fighting protective clothing for protection against these types of hazards, particularly during first response efforts to most emergencies [103]. As such, fire fighter protective clothing as well as other forms of protective clothing must possess some level of barrier performance to limit exposure to hazardous substances. Historically, the barrier function of clothing has been predicated on limiting water penetration for reducing potential scalding water injuries or prevent discomfort during cold temperatures [150].

In addition to providing a barrier in preventing the penetration of hazardous substances to inner layers of clothing or the wearer's skin, it also becomes important that the protective clothing limit contamination. The ability of protective clothing in terms of its design and materials to repel or shed liquids and to be easily cleaned or decontaminated is an essential feature for the safety and health of the individual firefighter. Further concerns exist for potential short and long-term effects of contamination on clothing and equipment materials.

Chemical Exposure and Contamination

Firefighters respond to a variety of incidents each presenting its own unique hazards. Structural fires have changed over the past several years because building materials have changed [32]. Roofing, insulation, carpets, paints and other construction materials all contribute to an ever growing diversity of chemical products founds at fires. The increased use of plastics and other synthetic materials release different kinds of combustion products, many of them highly toxic or carcinogenic [91, 24, 80, 137]. Some examples of fire combustion products include:

- Carbon monoxide and carbon dioxide,
- Inorganic gases (hydrogen sulfide, hydrogen cyanide, nitrogen oxides),
- Acid gases (hydrochloric acid, sulfuric acid, nitric acid),
- Organic acids (formic acid, acetic acid),
- Aldehydes,
- Chlorinated compounds (carbon tetrachloride and vinyl chloride),
- Hydrocarbons (benzene),
- Polynuclear aromatic compounds (PANs), and
- Metals (cadmium, chromium).

In addition, chemicals at the site of a fire further contribute to hazardous contaminants in fire smoke. A classic example is polychlorinated biphenyls (PCBs), found in electrical transformers and other equipment, which when burned may form dioxin, an acutely deadly substance [82, 48]. Even the normal household will contain cleaning supplies, pesticides, pool chlorine and other substances that contribute to release of toxic substances at fires. Table 2 lists some common fire smoke contaminants, the sources of these substances, and toxic effects from repeated or high concentration exposure to these chemicals [131, 111, 76].

Contact of these chemicals with fire fighting clothing can both penetrate and permeate protective fabrics. Since most firefighter protective clothing uses porous fabrics, the chemical vapors or liquids simply ***penetrate*** or pass through the pores of the material (Figure 4a). Molecules of chemicals can also ***permeate*** into the fibers or coatings of clothing materials and can remain in the material for long periods of time, depending on the types of exposure chemical(s) and care given to the clothing (Figure 4b). Chemicals that get into the clothing from either means can directly contact the wearer's skin [154, 124].

Table 2. Examples for Fire Contaminants

Contaminant	Sources	Toxicology
Polychlorinated Biphenyl (PCBs)	Power transformers/ capacitors Televisions Air conditions Carbonless copy paper Hydraulic systems Elevators	PCBs can produce dioxins which are toxic by inhalation & ingestion; PCBs also absorb through the skin; PCBs cause liver and pancreas damage.
Asbestos	Roofing and shingles Acoustic ceiling tiles Sprayed ceilings Old pipe insulation Old octopus type furnaces Pre-1975 drywall	Principal hazard is inhalation of fibers (<5 microns length) causes cancer; Asbestos fibers can be aerosolized from clothing & inspired or/ and ingested
Creosote	Power poles Railroad ties Treated wood or buildings Lumber yards Piers and docks	Creosotes is toxic through inhalation and skin absorption; Causes cancer of skin, prostate, and testicles
Plastic Decomposition Products - Polycarbonates - Polystyrene - Polyurethane - PVC	Electrical insulation Plumbing Furniture Construction materials Insulation and packaging Tools/ toys Automobiles	Variety of decomposition products including acrylonitrile, hydrogen cyanide, nitrogen oxides, hydrogen chloride, benzene; Various routes of toxicity through skin absorptions, inhalation or ingestion

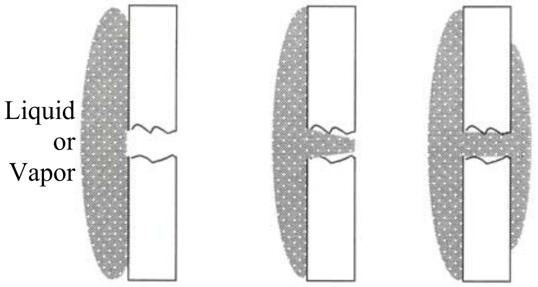


Figure 4a. Illustration of Chemical Vapor or Liquid Penetration Through Material.

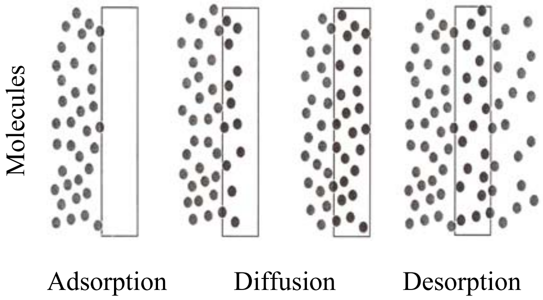


Figure 4b. Illustration of Chemical Permeation Through Material.

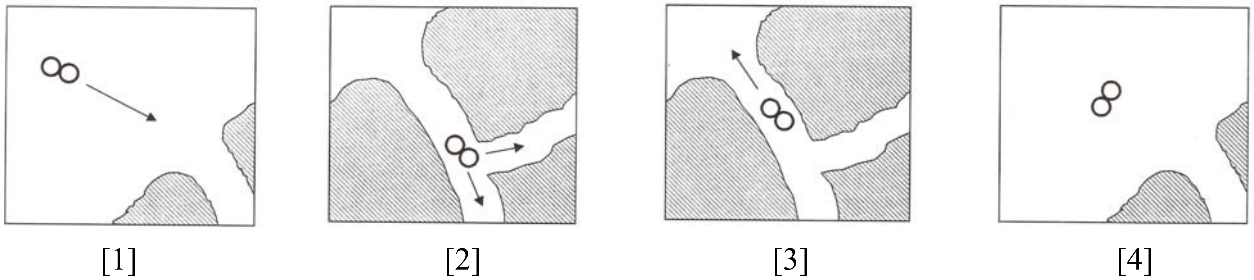
Different areas of the firefighter protective ensemble are likely to demonstrate varying propensities for the absorption or adsorption of chemicals. Any porous fabric material found in the clothing or other items may be contaminated. These include:

- Turnout clothing outer shells, moisture barriers, thermal liners, collars, and wristlets
- Station/ work uniforms
- Glove shells and liners
- Protective hoods
- Boot linings
- Helmet straps
- SCBA straps

Coated materials such as moisture liners, reflective trim, rubber boot outers, respirator masks are more likely to be affected by permeation. The same is true for hard plastics or resins such those used in the helmet, SCBA components, and certain turnout clothing hardware.

Particulate Exposure and Contamination

In addition to liquid or vapor chemical contaminants, a tremendous amount of ash, soot, and other solid matter are released during fires and fire fighting activities. This solid matter provides the visible portion of smoke and is the primary cause of residue left on structures and clothing following fires. Soot and ash represent incomplete products of combustion; that is, unburned fuel or agglomerated solids that fail to completely burn during the fire. During combustion, synthetic materials create an increase in the amount of particulate matter, hence the "black" smoke from burning plastics [137, 59]. Since soot particles are very porous, they tend to adsorb other hazardous chemicals as shown in Figure 5. Ash, resins, and other particles from fire smoke can easily become entrapped within the fibers of clothing. Accumulation of soot on protective clothing becomes visible as soiled or "dirty" areas. In some cases, these "soils" are made of melted resins or plastics that, in the heat of the fire, become liquid and spread even further throughout the protective clothing [137]. In other cases, many of the particles are too small to see (less than 10 microns) and can easily penetrate into the inner layers of clothing such as liner and barrier materials contacting the wearer's skin [154].



Fire gas molecule [1] next to pore in soot particle; [2] diffused into pore in soot particle; [3] diffuses out soot pore at later time; [4] (contaminant) released back to atmosphere.

Figure 5. Chemical Adsorption Process into Soot Particles

Firefighters may be exposed to other particulate hazards. Chemical dusts, lead particles, and asbestos may also be encountered at fires and other responses [59]. For example, though asbestos is principally an inhalation hazard, asbestos can cling to the protective clothing and the asbestos released poses a respiratory hazard when the responder removes his or her SCBA [64]. Similarly, lead and other toxic dusts can fill clothing pores and contaminate the firefighter's skin after the incident.

Biological Exposure and Contamination

The large proportion of medical aid calls for fire departments demonstrates the potential exposure to blood or other body fluids containing pathogens, particularly the Human Immunodeficiency Virus (HIV) or AIDS virus, and Hepatitis B and C viruses. These viruses are extremely small in size and are transmitted by blood or other biological fluids. The extrication of victims from automobile accidents and rescue of injured persons from fires and other incidents all involve the potential for this exposure. Even minute droplets of blood are capable of carrying thousands of virus [30].

On December 6, 1991, the Occupational Safety and Health Administration (OSHA) published a final rule on "Protecting Health Care Workers from Occupational Exposure to Blood Borne Pathogens" (29 CFR 1910.1030). This Final Rule states,

> "*When there is occupational exposure, the employer shall provide at no cost to the employee, appropriate personal protective equipment, such as, but not limited to, gloves, gowns, laboratory coats, face shields or masks, and eye protection, and mouthpieces, resuscitation bags, pocket masks, or other ventilation devices. Personal protective equipment will be considered 'appropriate' only if it does not permit blood or other potential infectious materials to pass through to or reach the employees work clothes, street clothes, undergarments, skin, eyes, mouth, or other mucous membranes under normal conditions of use and for the duration of time which the protective equipment will be used.*"

OSHA defines firefighters responding to medical emergencies as health care workers [100]. Therefore, the protective clothing they wear for such incidents must be capable of resisting the penetration of blood and other body fluids.

As with chemicals, most protective clothing readily absorbs blood. The effectiveness of clothing in preventing blood contact with skin depends on the type of clothing and materials used in its construction. Protective clothing can readily be contaminated with blood not only on the surface but on inner layers as well. Portions of the turnout coats such as the wristlets and the collar are particularly susceptible to this contamination because there are no barrier materials behind their knit material construction. Even though skin itself is a barrier to blood penetration, skin scratches and abrasions common during the rough physical environments of emergency response increase the risk for infection [55]. Even when clothing provides an adequate barrier, contamination of the outer shell of clothing can still constitute a health hazard as some biological agents may remain viable even after drying.

WMD Agent Exposure and Contamination

First responders in moderate to large metropolitan areas together with other sites of potential domestic terrorism opportunities are at risk to the unexpected release of WMD agents, which may be chemical, biological, or radiological in nature [41, 79]. Today, the most common chemical agents are those chemicals expressly selected and produced because of their ability to cause injury or incapacitation. Chemical warfare agents are generally classified into broad categories based on their intended use.

- Lethal agents
- Incapacitating agents
- Harassing agents

Another more recognizable categorization of chemical warfare agents is based on their physiological effects including nerve agents, blister agents, blood agents, choking agents, and irritating agents. Furthermore, threat analyses show that increasing risk from toxic industrial chemicals, which are common hazardous materials used in industry that pose the similar threats to emergency responders as the chemicals used and classified by the military as chemical warfare agents.

Biological agents pose a significant threat because their use is even more difficult to recognize than the use of chemical agents. The presence of symptoms may well be confused with a naturally occurring case or outbreak of disease. Many of the initial symptoms may be common to several other types of disease, which further complicates recognition, identification, and treatment. The ease with which people can travel throughout the world today presents a situation in which an individual can become infected in one part of the world and then carry the infection home before becoming symptomatic. The recent outbreak of the plague in India and the Ebola Virus in Zaire are examples of opportunities for a dangerous disease to spread. Fortunately, the diseases remained confined to the local area.

The use of radioactive materials in an unconventional attack via some dispersion mechanism, commonly referred to as a radiological dispersal device (RDD) or "dirty bomb," is widely recognized to have a greater likelihood of physical and social disruption than of lethal radiological consequences. However, the psychological and economic consequences of dispersal could be high and carry varying levels of risk to public health. The consequences depend not only on the radioactive material involved (its isotopic composition and physical form), but also the dispersal mechanism (explosive or non-explosive) and the environmental conditions under which it is released (e.g., urban, rural, weather). Thus, determining the absolute consequences of any potential dispersal in advance of its occurrence is not possible. Historically, exposure limits were established for the control and use of radioactive materials based on safety-basis accidents, including inadvertent exposure [79].

Hazards of Contaminated Protective Clothing

When protective clothing becomes laden with particles and chemicals, the clothing's performance is diminished in several ways:

1. Soiled turnout gear reflects less radiant heat. After materials are saturated with hydrocarbons, they will tend to absorb rather than reflect the radiant heat from the surrounding fire (the original color of the fabric will also affect radiant heat absorption).

2. Turnouts heavily contaminated with hydrocarbons are more likely to conduct electricity, increasing the danger to the firefighter entering a building or vehicle where wiring may still be live.

3. Clothing materials impregnated with oil, grease and hydrocarbon deposits from soot and smoke, can ignite and cause severe burns and injuries, even if the materials are normally flame resistant.

Even with the advent of specialized hazardous materials response teams within major fire departments, various chemicals can be encountered in normal fire fighting activities. Additionally, exposure to oils, fuels, and lubricants may occur around fire station vehicles. During responses, exposures to liquids ranging from pesticides to acids to chemical solvents may occur either knowingly or unknowingly. These exposures, in addition to being hazardous, can also degrade protective clothing material. For example:

- Clothing fabrics may become weakened and tear more easily.
- Thread or seam sealing tape may become loose.
- Water repellency treatments may be removed.
- Reflective trim can become less visible.
- Helmet shells/ face shield or SCBA masks visors may pit or craze.
- Clothing or equipment hardware may be corroded.

While several studies have examined clothing effects from use [153, 93, 83, 43, 139], little research has been made available to demonstrate the link between specific fire ground exposures and the effects on protective clothing and equipment.

Laboratory Tests for Chemical and Biological Resistance

Barrier testing approaches differ between establishing performance between chemicals and biological agents. In addition, there are differences between material tests and evaluations of clothing integrity for determining barrier effectiveness. The review of industry testing approaches and their limitations covered the following four areas:

1. Chemical resistance test methods
2. Biological penetration resistance test methods
3. Overall product barrier integrity evaluation techniques
4. Techniques to evaluate contaminant retention and removal

Detailed descriptions for the types of methods used, their application in the fire service industry, and the specific shortcomings in addressing firefighter and other first responder protection are discussed below.

Chemical Resistance: For chemical resistance, there are three types of material-chemical interactions:

- Degradation
- Penetration
- Permeation

Chemical penetration may be further distinguished by the state of the chemical penetrating the material - particulates (solids), liquids, and vapors.

Table 3 provides a list of the current test methods used for measuring chemical protective clothing performance and how both industry and end user organizations apply the information from these tests.

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

Chemical degradation resistance is determined by placing a piece of material in a chemical and observing/measuring the effects on the material at some period of time later. The effects may be visual, weight gain, amount of swelling or some measured property [34]. Many of the clothing, glove and footwear manufacturer degradation tables use qualitative rating systems to rank degradation performance as excellent, good, poor, or not recommended, however no uniform standard is applied to industry testing. Only recently has a new standard test for chemical degradation resistance been created (ANSI 105 for gloves), but industry has been slow to adopt it. Overall, chemical degradation resistance testing can be a useful means for screening chemical barrier materials [135]. However, degradation data can only be used to rule out candidate BCPC materials, not recommend a material. Degradation resistance testing is only currently applied to first responder protective clothing in the form of a precondition for emergency medical glove testing (exposure to alcohol is used a means to determine loss of glove material strength).

Degradation resistance testing is not a true barrier test; degradation testing does not indicate whether material will provide an effective barrier [114, 141]. Nevertheless, for many products, degradation resistance test data remain the only information available for the compatibility of biological or chemical protective products with specific chemicals and many end users base their clothing selection decisions on this type of information.

Table 3. Overview of Chemical Resistance Test Methods used for Protective Clothing

Property	Test Methods	Results	Industry Applications	End Users Applications
Degradation resistance	Industry practice	Visual changes, percent weight change, percent thickness change	Rubber glove, footwear, & splash suit manufacturers use information to create qualitative ratings for products. ANSI is not used.	End users examine ratings to determine compatibility of material for specific chemical
	Section 6 of ANSI/ ISEA 105-2000	Percent change in puncture force of exposed specimen		
Penetration resistance (particulates)	ASTM F1215	Percent efficiency for specific particle size	Used by some nonwoven material suppliers for claims related to particle hold out in 0.1 to 10 micron range	Some end users in remediation & chemical process industries use this data to compare products.
Penetration resistance (liquids)	ASTM F2130 ISO 6530 (runoff)	Percent repellency, absorption, & penetration	Rarely used by manufacturers; primarily an academic tool for evaluate protection from pesticides	Data is generally not available to end users.
	ASTM F903 (hydrostatic)	Visual penetration (pass or fail)	Used for structural, proximity, USAR, and splash protective clothing against selected chemicals	Few end users understand penetration & instead rely on degradation recommendations for low-end clothing use.
Penetration resistance (vapors)	No definitive test in industry (respirator cartridge protocols may be used)	Breakthrough time dependent on chemical concentration, flow rate, temperature, and humidity	Generally applied to absorbent-based materials for military & domestic preparedness	Only a few segments of market (law enforcement emergency responders) are aware of these data.
Permeation resistance	ASTM F739 (continuous contact) ASTM F1383 (intermittent contact) ASTM F1407 (gravimetric field test)	Breakthrough time Permeation rate Culmulative permeation dose (intermittent testing)	Majority of glove manufacturers & most high-end clothing manufacturers report permeation data for many clothing materials.	End users compare breakthrough times to select chemical clothing for severe exposure situations. Field testing is not performed.

Penetration Resistance - Penetration is defined as "the flow of chemical through closures, porous materials, seams, and pinholes and other imperfection in a protective clothing material on a non-molecular level." This definition is intended to accommodate particulates, liquids and gases, but most test methods focus on liquid penetration. Liquid suspended in air as aerosols and solid particles can also penetrate protective clothing materials, but specific industry test methods for particulate and vapor penetration have not been standardized.

Particulate penetration resistance of protective clothing materials is measured by exposing the material to an atmosphere containing particles. In some cases, the particles may be actual substances warranting specific attention (e.g., asbestos) while surrogate substances are used in other evaluation approaches (such as uniformly sized latex spheres or aerosols) [63, 155, 128]. Problems occur with measuring material performance because the majority of methods require some flow of air containing the particles through the material. If the material has poor air permeability, large pressure drops occur and materials are not tested consistently. Thus, choices exist for testing at a constant volumetric flow or constant pressure drop [128]. Particulate penetration is generally represented as an efficiency (percentage) for the material to hold out particles at specific size range. While researchers have devised a number of test approaches in this area, the protective clothing industry has not selected a preferred test method and end users generally accept material performance claims in the absence of standard test method. Specific test methods have not been adopted for the protective clothing used by the emergency response community.

Vapor penetration resistance testing also requires materials that have some air permeability and uses techniques similar to those applied to respirator cartridges, where materials are challenged with a chemical at a specific flow rate, concentration, temperature, and humidity [10, 40]. Vapor penetration can also be reported as the efficiency of removing chemical vapor, but is sometimes related to a service life or vapor breakthrough time. Since the majority of protective clothing for chemical vapor protection is film-based, this type of testing is usually limited to military applications where adsorbent-based materials are used for chemical warfare protection [46].

Two different approaches are used for measuring liquid chemical penetration resistance - runoff testing and hydrostatic testing. In runoff testing, a specified amount of chemical is poured over an inclined material sample and the retention of chemical in a blotter underneath the material sample is measured to determine the amount of penetration. Since the liquid that runs off can also be measured, an indication of repellency can also be made with this approach [28, 69, 81]. Nevertheless, runoff approaches for measuring chemical penetration resistance are perceived to be mild challenges of barrier performance [140]. In contrast, hydrostatic testing involves placing a material sample in contact with a liquid and attempting to push the liquid through the material using pressure. In this more severe test, the determination of material penetration is made visually. Testing is either performed by increasing the pressure until penetration is observed or under a specific set of exposure conditions [114, 96]. The latter approach is the most commonly used approach for reporting material chemical penetration resistance and has been applied to firefighter protective clothing using common fire ground chemicals (e.g., battery acid, surrogate gasoline, and hydraulic fluid). Figure 6 shows a common penetration test set up using ASTM F 903.

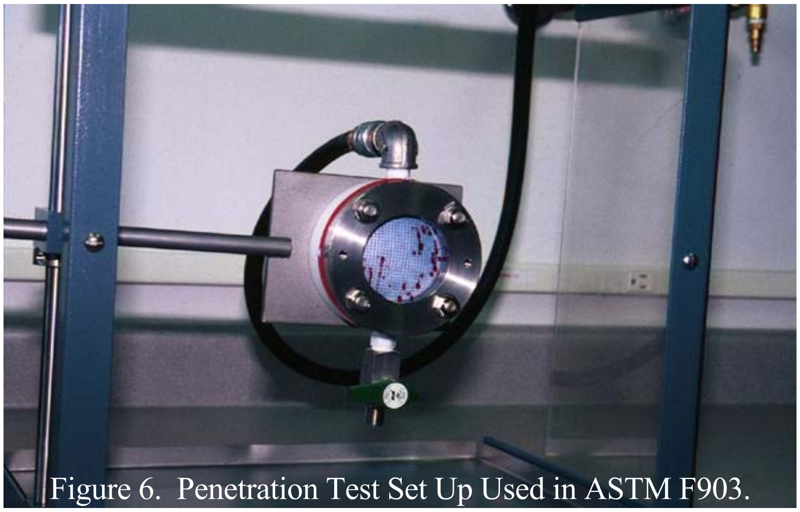


Figure 6. Penetration Test Set Up Used in ASTM F903.

While liquid penetration resistance testing provides an effective method for determining how well materials will hold out chemicals, it only pertains to bulk liquid penetration. Even if liquids do not penetrate, it is still possible that vapors can penetrate the material or the liquid or vapor permeates the material [114, 140]. For this reason, penetration testing is generally used for those chemicals where wearer exposure to the vapor is not a concern. The method has also served as an effective demonstration of seam and closure performance [25, 42].

Permeation Resistance - Permeation is a process in which chemicals move through a material at a molecular level. This process occurs as the result of chemical adsorption on the material outer surface, diffusion of chemical through the material, and desorption of the chemical from the material interior surface. The amount of permeation will be affected both by the physical and chemical characteristics of the chemical molecules compared to the structure of the material. As would be expected, larger molecular size chemicals will tend to permeate less than small molecules. Nevertheless, solubility effects of the chemical in the material also determine the extent of permeation [62, 61]. The greater the similarity of the material structure to that of the chemical, the more soluble the chemical will be in the material (of the principle, "like dissolves like") [115, 116].

Material permeation resistance is generally characterized using two test results:

- Breakthrough time – The time that chemical is first detected on the 'interior' side of the material. As discussed below, its determination is strongly dependent on how the test is configured and the sensitivity of the detector.

- Permeation rate – A measure of the mass flux through a unit area of material for a unit time. Permeation rate is most commonly expressed in units of micrograms per square centimeter per minute ($\mu g/cm^2 min$). For a given material-chemical combination, the steady-state or maximum observed permeation rates are usually reported.

Permeation testing involves the use of a test cell is used for mounting the material specimen. The test cell consists of two hemispherical halves divided by the material specimen. One half of the test cell serves as the "challenge" side where chemical is placed for contacting the material chamber. The other half is used as the "collection" side that is sampled for the presence of chemical permeating through the material specimen. The basic procedure in each test is to charge chemical into the challenge side of the test cell and to measure the concentration of test chemical in the test cell as a function of time [67].

Although the permeation test procedure is simple in concept and generalized procedures are specified by standard test methods, a number of significant variations exist in the manner in which permeation testing can be conducted [126, 95]. These variables include:

- The general configuration of the test apparatus.
- How the chemical contacts the material specimen in the test cell.
- The type of collection medium used and frequency of sampling.
- The type of detector and detection strategy used.
- The test temperature.

The industry has moved to a standard test cell, but for highly hazardous chemicals, relatively small test cells are desired [26, 66, 149]. The configuration of the test apparatus may be open-loop where the challenge side of the test cell is continually flushed with the collection medium, or closed-loop where permeating chemical accumulates in the collection medium. The interval of sampling will affect how precise the breakthrough time will be determined but is also affected by the choice of detector, which in turn is partly dictated by the test chemical being evaluated. Temperature is known to have a significant effect on permeation results. Small variations in temperature can create large differences in breakthrough times and permeation rates [113, 148, 160].

Permeation resistance testing is the appropriate test when vapor protection is required. This does not mean that the test can only be applied for gas or vapor challenges, but rather that the test discriminates among chemical hazards at a molecular level owing to the sensitivity for detecting permeating chemical in its vapor form (as opposed to liquids or solids). As such, permeation testing represents the most rigorous of chemical resistance test approaches.

Within the protective clothing industry, many end users judge the acceptability of a material on the basis of how its breakthrough time relates to the expected period of exposure. Reporting of permeation rate offers a more consistent and reproducible means of representing material permeation. The inherent variability and test system dependence on breakthrough times make this data a less than satisfactory choice for characterizing material performance [126]. In contrast, permeation rate data can be used to show subtle changes in material characteristics and determine cumulative (total) permeation when acceptable "dose" levels of the test chemical can be determined. On the other hand some material-chemical systems take a long time to reach steady-state or exceed the capacity of the detector. In addition, the lack of widespread data on acceptable dermal exposure levels for most chemicals leads many protective clothing specifiers to rely on breakthrough times exclusively.

The flexibility of most permeation tests allow testing laboratories or end users to choose those conditions which best represent the expected performance of the material. Usually, the primary decisions in specifying permeation test involve the following:

- The chemical and its concentration.
- The state and periodicity for contacting the chemical with the material.
- The material and its condition prior to exposure.
- The environmental conditions of the exposure.
- The length of the test.
- Sensitivity of the test system.

The majority of permeation tests in the protective clothing industry are conducted using neat chemicals continuously contacting pristine material at room temperature for a period of 8 hours. Test sensitivities are at 0.10 $\mu g/cm^2 min$ or better are used but may be higher for difficult-to-evaluate chemicals [126]. Other barrier materials are generally evaluated against chemicals for longer period of times at slightly elevated temperatures for examining steady state permeation rates and cumulative permeation. These test conditions are considered worst case, because constant contact of the material with the chemical is maintained which may or may not be representative of actual use. When specific barrier product applications are identified, it is best to model the conditions of use through the selection of test parameters. If general performance is to be determined, using industry practices for test set up are preferred so that material performance may be compared against other available data.

Permeation data is often inappropriately used. For example, permeation data may be used to select a material for non-skin toxic, non-volatile chemicals, or when the principal exposure to the wearer will be areas that are not protected. Reliance on permeation data for generic polymer materials is extensive within industry, especially given the availability of quick selection guides [127, 49]. However, these ratings do not account for differences in material thickness and formulation [77, 125]. Furthermore, significant variability of permeation for clothing products of the same generic class has been shown [99, 113].

Despite the complexity and shortcomings of permeation resistance test, the permeation test is the principal chemical resistance test applied to protective clothing involving high levels of risk for chemical exposure, such as protective clothing used in hazardous materials emergencies. The application of permeation data to more ordinary forms of firefighter protective clothing would be inconsistent with the levels of garment integrity where vapors and gases could freely penetrate these types of clothing. However, with concerns for first responder safety involving chemical agent testing and toxic industrial chemicals used in domestic terrorism, new approaches are needed to properly evaluate clothing materials for these more rigorous forms of barrier performance.

Biological Penetration Resistance: Biological hazards can encompass a wide variety of different occupational settings ranging from bloodborne pathogen exposure to contact with molds to biotoxin. Biological barrier properties include:

- Microorganism filtration efficiency
- Biological fluid resistance

- Biological fluid and viral penetration resistance
- Antimicrobial performance

Industry testing approaches vary, but the many of the biological barrier methods are similar to those methods used for chemical resistance of protective clothing materials. Table 4 summarizes some of the test methods used for these performance properties.

Table 4. Overview of Biological Penetration Resistance Test Methods Used for Protective Clothing

Property	Key Test Methods	Types of Results	How Applied by Industry	How Applied by End Users
Microorganism filtration efficiency	ASTM F1608 ASTM F2101	Percent hold out of microorganism or log reduction in microorganism challenge	Primarily used in relation to surgical masks; only clothing application in military for biological warfare agents	Mask effectiveness compared on basis of percent effectiveness; but not treated as respirator
Biological fluid resistance	AATCC 42	Percent material weight change	Used as the basis for a low end claim for gown or garment performance	Information from tests is quantitatively used to compare material offerings by manufacturers
	AATCC 127	Pressure at which fluid visually penetrates	Used as a basis for a middle range claim for clothing performance	
	ASTM F1819 ASTM F1862	Visual penetration at specific test pressure	Used for materials which do not pass biological fluid resistance tests or facemasks	Little user awareness of tests or pressures
Biological fluid penetration resistance	ASTM F1670	Visual penetration (pass or fail)	Used primarily as screening test for viral penetration resistance	Test may be specified for materials that fail viral penetration resistance
Viral penetration resistance	ASTM F1671	Microbiological assay indicating number of virus passing through material	Used to establish liquid proof claims; applied for first responder protective clothing utilized for emergency medical applications	End users perceive materials passing test as having highest barrier qualities for protecting against bloodborne pathogens
Antimicrobial activity	AATCC 100 AATCC 147	Percent change in microorganism concentration	Tests rarely used in conjunction with barrier claims	Little or no end user knowledge of tests for apparel

Microorganism filtration efficiency - Microorganism filtration efficiency tests evaluate the ability of BCPC items and fabrics to prevent the passage of airborne microorganisms. For the most part, testing for air-borne microorganism penetration through protective clothing is associated with respirator performance. However, concerns for exposure to bioterrorism agent have prompted further attention to this area of clothing performance in a similar manner as exists for asbestos and lead dust exposure. Keeping microorganisms off the skin is important so that re-exposure to the same contaminants can be avoided.

The testing of material performance for microorganism filtration efficiency determines the percentage of microorganisms for a given size that will penetrate fabric or fabric seams. Alternatively, results are recorded in terms of logarithmic reduction values (LRV) for better performing materials. This testing is similar in principal to particulate penetration resistance with the exception that microorganisms are used in place of particle or aerosol challenges [117, 29]. Some common microorganism challenges include:

- *Pantoea agglomerans* (a bacterium widespread in the environment recovered from a variety of plants with cells that are 0.6 μm to 1 μm in diameter and 1.2 μm to 3 μm long
- *Bacillus subtillis* var. *niger* (rod-shaped spores, measuring 0.95 μm to 1.25 μm long and 0.55 μm to 0.70 μm wide)
- *Staphylococcus aureus* (a rod-shaped bacterium with a mean diameter of 3 μm)
- Bacteriophage Phi-X174 (a viral surrogate with diameter of 0.027 μm)

The choice of the microbiological agent, its method of suspension (usually as a liquid aerosol), and its concentration or titer in the suspension affect the type of challenge.

Currently outside the military, the clothing industry has only applied this testing technology to face mask materials used in surgery or other medical applications. Very little work has been done to use microorganism filtration efficiency tests for apparel.

Biological fluid resistance - Biological fluid resistance testing discriminates barrier characteristics of different fabrics used in apparel for preventing blood or other body fluid strike-through (fabrics with fluid resistance may still allow fluid penetration under some use conditions). Test methodologies, similar to water and liquid penetration resistance, are used for determining if blood, body fluid, or surrogate liquids will pass through the fabric [65, 98]. In many of these tests, synthetic blood or other liquids with low surface tension emulating blood properties are used, although inferences are often made based on testing with water [29]. These tests are used for clothing materials that do not successfully "pass" the biological fluid penetration resistance tests [30]; however, there is no agreement on the specific tests or performance levels for demonstrating this type of barrier performance.

Biological fluid and viral penetration resistance - Biological fluid penetration resistance tests evaluate the ability of materials to prevent penetration of biological fluids into the PPE (biological fluid penetration resistance testing differs from biological fluid resistance testing in that it provides more of a 'proof' type determination). Generally applied to clothing, this testing involves hydrostatic-based methods where a surrogate fluid representing the characteristics of blood is pushed against the material at a given pressure. Visual observations are used to determine if the biological or surrogate fluid passes through the material.

Similarly, viral penetration resistance testing evaluates the ability of materials to prevent the passage of virus or related microorganisms. Viral penetration testing involves an increased level of sophistication over biological fluid penetration resistance testing. Non-pathogenic microorganisms having similar morphology and size as blood borne pathogens are used in the challenge fluid and specific assay techniques are used to quantify the number of microorganisms that penetrate the material over a given time period and set of exposure conditions [29].

The type of fluid and the conditions of exposure influence the penetration of the fluid through a material. Blood and other body fluids have lower surface tension than water and will tend to penetration materials more readily. Surface finishes on the material will affect the penetration process. In addition, the pressure and length of contact time of the material with the fluid will also affect biological fluid and viral penetration resistance [3, 129, 88, 87].

A hierarchy is established between the two types of tests since bloodborne pathogens can only move in the presence of liquid. Materials that show no visible penetration of a biological fluid may fail a related microorganism-based penetration resistance test under the same circumstances since very small liquids may still pass through a material and go unobserved. However, materials that pass the microorganism-based penetration resistance test will show no visible penetration of the biological fluid, assuming that all other conditions (including the characteristics of the fluid) are identical [29, 97]. This hierarchy is significant because it demonstrates that large numbers of microorganisms may penetrate a material without obvious signs of protective clothing material failure [29, 85].

The biological fluid and viral penetration resistance tests are extensively used throughout the medical and emergency response industries for demonstrating the effectiveness of clothing materials in preventing penetration of blood and other body fluids that may contain bloodborne pathogens. The biological fluid resistance test is based on synthetic blood (which mimics blood's red color, surface tension, and viscosity) while Bacteriophage Phi-X174 is used as a surrogate for Hepatitis virus and HIV [29, 65]. Given the relatively small size of the viral surrogate, claims for other bloodborne pathogens are generally made based on the performance of materials when challenged by Bacteriophage Phi-X174. End users only appreciate this level of performance when they perceive the risks for pathogen exposure to be high; otherwise many end users feel satisfied with fluid resistance performance of clothing.

Antimicrobial performance - In barrier evaluations, antimicrobial performance testing evaluates the ability of protective clothing items or materials to kill microorganisms upon contact. Given the wet conditions of use for protective clothing, it is important that clothing items not harbor or promote the growth of microorganisms. While much of the antimicrobial performance of clothing and other items is related to care and much as any other factor, the use of chemical antimicrobial finishes can help eliminate the growth of undesirable microorganisms. Antimicrobial finishes can also be used in conjunction with different types of barrier materials for providing viral or bacterial penetration resistance [36].

Antimicrobial tests involve inoculation of the protective clothing material with a specific microorganism. Generally, microorganisms of interest are bacteria and fungus, and will include suitable species of microorganisms depending on the intended use of the protective clothing item. The inoculated clothing material is incubated for a specified period and the remaining microorganisms on the material are eluted for assay. The results are reported as the percent or logarithmic reduction of the microorganism.

There is little awareness of antimicrobial activity as a barrier performance claim among end users. Most work in this area is related to preventing mildew or fungal growth, though new technologies applied to apparel now incorporate materials with demonstrated antimicrobial activity.

Overall Product Integrity Evaluation Techniques: Overall product integrity performance testing provides a determination of how well the protective clothing prevents substances from entering (or leaving) the protective clothing through the material, seams, closures, or any other parts of the protective clothing that are evaluated. In general, whole items of clothing or equipment (garments, gloves and footwear) are evaluated as opposed to materials or parts of garments. In this fashion, overall product integrity is able to assess the protective qualities of the entire clothing item. The three types of integrity testing include:

- Particulate integrity
- Liquid integrity
- Gas/vapor integrity

Integrity testing is primarily intended to evaluate the overall design of protective clothing in being leak free, especially for those parts of the product that cannot be easily assessed with smaller scale chemical resistance or biological barrier tests. These parts include the seams, closures, and interface areas of protective clothing. Integrity testing can also be applied to complete ensembles of different protective clothing items.

When integrity testing is conducted using human test subjects, the amount of test variability is increased, but the testing provides a more realistic assessment of how the protective clothing will perform under actual use conditions.

Table 5 provides a summary of the test methods used for integrity testing.

Particulate Integrity - Particulate integrity testing determines if particles enter or leave whole items of protective clothing. In this testing, garments are worn by test subjects in closed chambers filled with a particle challenge such as an aerosol. In some applications, the inward leakage of particles into the clothing is measured, as would be the concern for working in environments involving contaminated dust or other solid particles (asbestos fibers, lead dust, and beryllium dust). The object of the clothing may simply be to keep the particles off the skin to prevent their re-release in exposing the wearer's respiratory system.

Table 5. Overview of Whole BCPC Item Integrity Test Methods

Property	Key Test Methods	Types of Results	How Applied by Industry	How Applied by End Users
Particulate integrity	ISO 13982-2	Percent inward leakage or intrusion coefficient	Test approach is rarely used to qualify clothing for particulate environments, except in clean-room environments where industry-specific tests are used	End users have little awareness of whole garment particulate integrity; instead rely on creating secure interfaces by use of tape
Liquid integrity	ASTM F1358 ISO 17491	Visual pass or fail; amount of liquid on inner garment	Test is only used in conjunction with NFPA clothing specifications for emergency response applications	Little end user awareness of test outside emergency response industry; many users do not like the impact of test on clothing design
	ASTM D5151	Visual pass or fail	Applied to all medical gloves on statistical basis; used to establish waterproof performance claims; little used for chemical gloves	End users specify gloves using standards that include tests in medical applications; expect performance for other gloves
Gas/ vapor integrity	ASTM F1052 ISO 17491	Ending test pressure (pressure drop)	Extensively used by manufacturers for the testing of totally-encapsulating suits; in some cases, the test is applied to all suits before sale; manufacturers sell test kits for end user testing	The test is part of the normal acceptance and care procedures for most encapsulating suits by end users
	29 OSHA 1910.120 (Appendix B)	Percent inward leakage or intrusion coefficient	Test is specified for upper end protective clothing in emergency response applications; also used by military for chemical warfare applications	Limited testing performed by end users for encapsulating suits with ammonia in manner like respirator fit testing; otherwise little use of test

Industry has little experience with particulate integrity testing in the United States. Typically results for fabric and garment performance do not match since materials that have high particulate penetration resistance actually result in more airflow through garment seams, closures, and interface areas causing a higher level of particulate leakage into the garment [90]. Unless the garment also has gas/vapor integrity, some exposure to particulates may be assumed since air flow into the garment (carrying particles) can be created by wearer movements. Yet, particulate challenge testing has assumed a higher level of performance with concerns for first responder exposure to bioterrorism agents such as anthrax and the potential for release of radiological particulates during a dirty bomb detonation.

Liquid Integrity - Liquid integrity testing determines if liquid enters to the interior side of the protective clothing or onto wearer underclothing when the exterior of the clothing is exposed to a liquid challenge. Different testing approaches assess how liquid sprayed onto or contacting the clothing exterior can enter the clothing, particularly through seams, closures, and interface areas with other equipment [142, 156]. The most common forms of this test are done statically with the clothing placed on manikin. Underneath the clothing, a liquid-absorbing inner garment is placed to show spotting of the test liquid that penetrates. Though water is the principal challenge in this testing, it is often treated with a surfactant to increase the severity of the test, as lower surface tension allows liquids to penetrate openings more easily. The length of the testing is also usually extended so that protective clothing design problems or defects will easily show up on the inner liquid-absorbing garment [142]. Test results are reported as pass or fail depending on the detection of liquid marks on the liquid-absorbing inner garment. Any detectable amount of liquid constitutes failure.

Figure 7. Liquid Integrity Test Used for Firefighter Protective Clothing

Many manufacturers consider liquid integrity testing to promote clothing designs that are considered unacceptable to end users, primarily in terms of thermal comfort, because of the design features that must be implemented to prevent liquid leakage, particularly at closures and interface areas. Manufacturers would instead prefer to rely on material testing for product barrier claims, while end users tend not to question problems with garment designs that fail to provide liquid integrity.

Despite issues related to manufacturer and user acceptance, liquid integrity testing of garments using static manikins has become a mainstay performance test for firefighter and other first responder protective clothing, including protective clothing for structural fire fighting. In its application to firefighter protective clothing, special allowances are made to close off areas next to interfaces or for some liquid travel into the garment, but not onto the manikin's skin or liquid absorptive garment. For example, a plastic bag is taped over the manikins head and down over a large portion of the garment collar to prevent leakage through the top of the garment. The testing has only been applied to the garment, not the entire ensemble, and therefore a true assessment of overall user protection from liquids is not completely demonstrated.

Liquid integrity testing is also applied to items of gloves and footwear to substantiate water or liquid-proof claims. For example, all medical gloves must meet an acceptable quality limit (statistic basis of a claim) for testing that involves filling gloves with 1000 mL of water and observing the gloves for leakage. Versions of this testing are also applied to firefighter and other first responder gloves and footwear to demonstrate liquid integrity, usually after some preconditioning of the item to simulate wear or use. The sensitivity of this testing for evaluating leakage has been investigated to identify the size of hole or defect that results in failure and its correlation with other material-based tests [30, 84, 121]. Despite findings that many defects in barrier clothing can go unnoticed with this form of liquid integrity testing, the protective clothing industry continues to use overall testing of gloves because of its relative simplicity, low cost, and ease of interpretation.

Gas/Vapor Integrity - Specialized testing determines if gas or vapors can penetrate protective clothing. This testing is applied to generally totally-encapsulating chemical or biological protective suits, gloves, and footwear that are intended to provide a complete vapor barrier around the body or portion of the body covered. Simple inflation tests may be performed to determine if any parts of the item leaks simply by noting the pressure drop in an item as an indication of leaking. In this type of integrity testing, the garments are inflated to one pressure, lowered to a "test" pressure and then observed over a period of time to determine if any change in pressure occurs [52]. Most test approaches set minimum pressures to and criteria for an acceptable pressure drop to adequately identify protective clothing leakage [31]. If a clothing item does leak, brushing a soapy water solution over the suspected portions of the item can identify the area(s) of leakage. However, this approach can only work on encapsulating clothing that employs an outer film surface as the pressure barrier for the product. In addition, because the test requires that all designed openings be plugged or seals (i.e., exhaust values or closures), some aspects of the clothing are not evaluated.

Alternatively, testing may be performed with human subjects performing exercises in the clothing within a gas/ vapor-filled chamber to provide a dynamic assessment of gas/ vapor penetration resistance. Ammonia and sulfur hexafluoride are two commonly used challenges for this type of testing. In this testing, the internal concentration of the contaminant is measured and compared to the challenge concentration [45]. Results are generally reported as an intrusion coefficient (the percentage of challenge leakage into the suit). In some variants of this testing, special patches are placed on the test subject that adsorbs the challenge contaminant (such as methyl salicylate). In this fashion, the testing simulates the way that a chemical would be absorbed through the skin. The latter testing is used as part of Man-In-Simulant Testing (MIST) to evaluate the effectiveness of protective clothing ensembles against certain chemical warfare agents. Evaluations based on MIST have been used for characterizing firefighter and other forms of first responder protective clothing for integrity against nerve agents [89, 70].

Techniques to Evaluate Contaminant Retention and Removal: The principle of a material being an effective barrier against a specific substance does not always translate into the product also minimizing the retention of contamination or permitting its easy removal. Certain material characteristics such as polymer type, the type of surface finish, and wettability or absorption resistance affect the ease to which contamination will remain in the clothing material. However, for firefighter protective clothing that consists of multiple material layers with varying design features, the propensity to resist contamination will differ with the specific portion of the clothing exposed. Certain clothing components such as the shell fabrics are typically treated with water-resistant finishes, which in addition to repelling water, further act to shed different liquids. The durability of these finishes are affected by wear and their effectiveness to liquids other than water will depend on the liquid's surface tension and degradation effects, if any, with respect to the challenged material. Firefighter protective clothing is tested for water absorption resistance using a runoff style test where water retention in shell fabrics is measured gravimetrically after sample fabric has been washed to partially assess durability of the finish. The specific test used in this evaluation involves a 500 mL application of water on the inclined surface of the material. The test has been criticized as representing too weak of an exposure to completely characterize the range of liquid contaminants and types exposure to which clothing is normally subjected.

Evaluating Effects of Dosing and Sweat on Materials Barrier Performance: The majority of barrier performance tests allow the variation of challenge levels for determining the effectiveness of sample materials in preventing chemical or biological agent penetration. The chemical degradation and penetration tests are liquid exposure tests and can be performed with any type of liquid with different levels of dilution or with the modification of the exposure time to determine the effects of chemical or materials or under what conditions the material will hold out liquid. In general, liquid penetration testing can measure both degradation effects and penetration times. Neat liquids are generally used to examine the specific effects of degradation couple with liquid hold out. Vapor penetration testing can be conducted with the chemical at any level of dilution, though challenge levels are best set at expected maximum concentrations for the application to minimize the need for multiple tests, as this testing must be performed for several different chemicals to understand the barrier effectiveness of candidate materials. The current method for applying the chemical permeation test permits the testing of candidate materials for different concentrations of chemicals and involves a similar strategy for selection chemical concentrations representing the anticipated maximum exposure levels. Biological barrier does not typically allow for varying the exposure levels as standardized tests for measuring hold out of liquids containing microorganisms to be provided at specific titers (concentration levels) owing the methods used for growing viable surrogate organisms. This principle also applies to airborne pathogens using viral or bacterial surrogates. One exception to this limitation occurs when small particles are used in place of biological organisms for modeling airborne pathogen penetration. However, the same general approach is recommended for evaluating materials at the expected maximum concentration of agent. It is also possible to determine the effects of multiple (repeated) exposures for those materials, which use reactive or adsorptive technologies, by choosing a series of challenging by varying exposure concentration and time. These tests are not standardized and must be specifically developed based on the expected application.

Adding expected levels or moisture or sweat into the material prior to barrier testing can examine the impact of moisture or sweat in the material system. A number of procedures have been developed for introducing moisture in fire fighter clothing materials to simulate its effects on heat transfer. Adaptation of these methods using similar techniques can be applied as a precondition to most barrier testing for those material systems that employ reactive or adsorptive materials.

Tests for Material Biocompatibility: The potential for material effects on the individual wearer can be determined using standard tests, generally applied to the evaluation of medical devices. Specifically, it is recommended that the materials used in fire and emergency service protective clothing be classified as "external devices that contact breached or compromised surfaces for limited exposures" and be recommended for the appropriate evaluations in accordance with AAMI/ANSI BE 78, Biological Evaluation of Medical Devices, Part 10: Test for Irritation and Sensitization [1]. This standard specifies procedures for determining the sensitization and irritation of skin using prolonged exposures with animal testing, and is the current minimum testing that is recommended for materials used in the construction of related, medical products, such as surgical gowns and masks.

Research Needs

A review of the test methods that are used for characterizing the chemical and biological performance of firefighter protective clothing reveals a number of gaps and specific test needs to address the full range of barrier performance needed by firefighter first responders. The proposed test method development focuses on WMD protection; however, additional tests are needed to improve current methods of determining ensemble integrity to conventional fireground chemical and biological hazards. This review has identified the following specific areas where research and development are needed:

1. The establishment of permeation test conditions for chemical warfare agents and toxic industrial chemicals which better mimic expected exposure conditions. The levels of acceptable barrier performance should be established based on an analysis of permissible skin exposure levels for each of the specific agents and chemicals tested.

2. The industry lacks standardized methodology to examine the barrier effectiveness of materials to particulate hazards. A benchscale test method is needed to evaluate material resistance to particulate penetration consistent with use practices that does not depend on filtration-based approaches.

3. A companion overall integrity test method is needed to evaluate whole garments and ensembles for inward penetration of particulates. The test method should permit the evaluation of complete ensembles under dynamic conditions in a manner that the technique itself does not compromise the garment or ensemble.

4. The current liquid integrity test should be adapted and expanded to permit evaluation of the entire ensemble under dynamic conditions. The existing embodiment of the liquid integrity test involves the use of static manikin and specialized blocking of the garment to limit the evaluation to garment seams and closures. Modifications to the test should be investigated to assess complete ensemble performance and permit quantitative determinations from the test.

5. The MIST evaluation protocol should be standardized for providing a means for testing the aerosol or vapor integrity of firefighter and other first responder ensembles to determine overall integrity against WMD agents and chemicals. The existing protocol varies with the testing facility and has limited access to industry.

6. A series of tests should be developed to better evaluate the contamination retention or ease of decontamination for firefighter protective ensemble materials and systems. These tests should quantify the amount of contaminant retained in clothing as well as permit the assess for contaminant removal from clothing with conventional cleaning and decontamination methods.

CHAPTER IV

HEAT STRESS AND COMFORT

Many of the inadequacies of current protective gear for first responders can be associated with heat stress and discomfort, resulting from hot, bulky protective garments. The additional need for barriers to protect against chemical and biological hazards increases the challenge of creating comfortable, functional protective clothing. Advanced protective ensembles must minimize heat stress while providing protection. The impact of protective clothing on heat stress depends on the extent to which the clothing affects the heat transfer between the first responder and the environment. The breathability, or moisture vapor permeability of the clothing, can affect the evaporation of moisture from the body and heat exchange. Clothing weight, stiffness, and bulkiness add additional burden that can increase metabolic heat production in the stressful conditions typically associated with firefighting and emergency response.

Protective clothing systems for firefighters and other emergency responders impose, by their unique and often contradictory sets of properties, a metabolic and sensory burden that in many cases impedes performance and safety. Heat stress is a significant risk for first responders involved in strenuous activity, especially in hot and humid environments. The primary goal of testing and evaluation is to provide a systematic way to assess the impact of protective clothing on heat stress.

In order to include heat stress and comfort as design parameters in the development of advanced protective ensembles for first responders, it is necessary to be able to measure and evaluate these factors. This report will focus on describing the laboratory test methods that are currently available for this purpose, and on identifying research needed to advance the state of these testing technologies and protocols.

Background

A state-of-the-art testing approach for heat stress and comfort must be based on a multilevel concept, advancing from the measurement of constituent fabric heat/moisture transfer properties to, ultimately, the analysis of complete garment properties. Consequently, the following levels of testing and evaluation must be considered:

- Heat and moisture transport properties of fabrics.
- Heat and moisture transport of garments and predicted heat stress limits using a sweating instrumented manikin.
- Controlled, human wear trials in an environmental chamber.
- Field tests, conducted in actual use conditions.

These elements must be interwoven in stages to produce a database on the protective clothing system properties that translate to performance in the field.

Laboratory Tests for Clothing Heat Stress

Several testing technologies that have emerged can be used to critically assess materials. Most significant of these are guarded sweating plates for small samples and sweating thermal manikins for complete ensembles.

Sweating Hot Plate Tests

Sweating hot plate tests are the most widely used instrument means of measuring the heat and moisture vapor transfer properties of materials used in protective garments. These tests measure the dry thermal resistance (insulation) and the evaporative resistance of fabrics. Sweating hot plate test methodologies have been available for many years and are standardized by the American Society for Testing and Materials (ASTM) and the International Standards Organization (ISO). The most comprehensive standardized method is ASTM F1868, Standard Test Method for Thermal and Evaporative Resistance of Clothing Materials Using a Sweating Hot Plate [6, 55].

As a result of incorporation into NFPA standards, sweating hot plate methods are increasingly used in the United State to quantify the heat stress potential of materials used in protective clothing for firefighters and other emergency responders. ASTM F1868, Part C (Procedure for Total Heat Loss in a Standard Environment) is referenced in several NFPA standards, including NFPA 1951, 1971, 1977 and 1999, as a basis for specifying heat stress performance in protective clothing used by firefighters.

A sweating plate test apparatus consists of a guarded flat plate housed in an environmental chamber.

Figure 8. Guarded Sweating Hot Plate in Environmental Chamber

The plate is electrically heated to skin temperature (35ºC) and covered by the test material. The side of the fabric that normally faces the human body in wear faces the plate. A guarded ring, heated to the same temperature as the test plate, prevents lateral heat loss. Water is fed to the surface of the test apparatus that is covered by a moisture vapor permeable cellophane sheet in order to shield the fabric from liquid water.

The entire test apparatus is housed in an environmental chamber to provide for testing in a controlled ambient condition. ASTM F1858, Part C, specifies ambient air temperature and humidity at 25ºC, 65% RH. These conditions create thermal heat loss through the test fabric, or heat loss that is influenced by both the dry thermal insulation and evaporative resistance of the test material. Measurements are made under both dry and simulated sweat wetted skin conditions. Dry tests are conducted to determine conductive thermal resistance. Wet tests are conducted to determine apparent evaporative thermal resistance. The total heat loss of the test material is calculated using an equation that combines both conductive and evaporative heat transfers as:

$$Q_t = \frac{10°C}{R_{cf} + 0.04} + \frac{3.57\ kPa}{R_{ef}^{A} + 0.0035}$$

Where: Q_t = total heat loss (W/m^2),
R_{cf} = average intrinsic thermal resistance the laboratory sample (Km^2/W), and
R_{ef}^{A} = average apparent intrinsic evaporative resistance of the laboratory sample ($kPam^2/W$).

The sweating plate method specified by NFPA standards is a non-isothermal test. Other sweating plate protocols, including ASTM F1868, Part B and ISO 11092 [75], measure evaporative resistance using isothermal conditions (the sweating plate and ambient air temperature are both set at 35ºC). The rationale for use of isothermal testing conditions is that it eliminates complications that can be involved in measuring evaporative resistance across a fabric due to moisture condensation in the fabric layers. However, the non-isothermal procedure, specified in the NFPA standards, has the advantage of being a more realistic simulation of total heat loss from sweating skin into a cooler environment.

Sweating Manikin Tests

Sweating hot plate tests, made on flat fabric samples, cannot provide information critical to garment design. Sweating plate tests cannot validate the effects of garment fit, seaming and joining and pumping effects from articulation and movement. This is an important consideration since the overall heat stress burden of protective clothing is determined, not only by the breathability of constituent fabric components, but also by air layers trapped inside the clothing. The air volume in the protective ensemble is determined by the garment design and fit. In addition, sweating plate tests do not account for the effects of additional layers, such as reinforcements, padding, trim or the like. Therefore, a major gap exists in available data for realistic research on the heat stress associated with protective clothing systems. Sweating manikin tests provide opportunity to address this shortcoming in instrumented approaches.

The "Coppelius" type sweating manikin is an example of advanced sweating manikin technology.

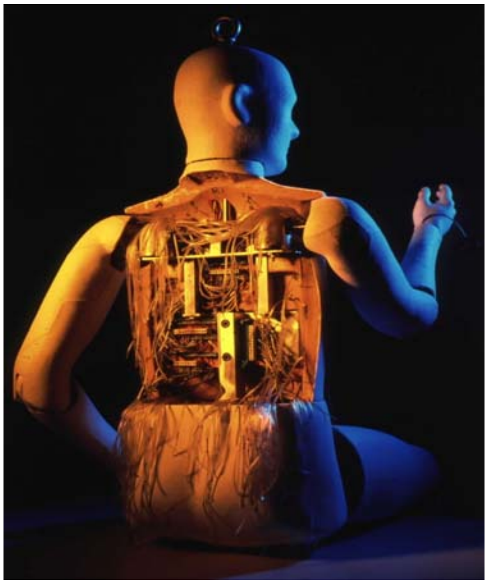


Figure 9. Sweating Manikin

The main features of this sweating manikin technology are:

- A computer controlled heating system with 18 individually controlled body sections.
- A computer controlled sweating system with 187 individually controlled sweating glands; sweating over the whole body with the exception of head, hands, and feet.
- Anatomical body dimensions, size 40.
- Prosthetic joints to permit movements and different postures.

The manikin is housed in a climatic chamber. Water is supplied from a reservoir, placed on a balance near the ceiling in the chamber. A micro-valve system in the manikin distributes the water to the 187 sweat glands, and the computer system allows individual control of each sweat gland. The condensed water on the dressed manikin is recorded by measuring the change in the weight of the clothed manikin during the test. This measurement is made from the output of the sensitive balance from which the manikin is suspended. Test garments are weighed before and immediately after the test. This is done to estimate the amount of moisture condensation in the individual clothing layers. Moisture condensation in the skin material of the manikin is calculated as the total weight change subtracted by the moisture condensed in the clothing.

Because of the complex nature of sweating manikins, successful installation and operation of these facilities requires a high level of specialized expertise and sophisticated laboratory support infrastructure. Nevertheless, laboratory facilities throughout the world currently use instrumented sweating manikins to evaluate the heat stress potential of clothing. Existing sweating manikin technologies are different with respect to specific details of the manikin test apparatus. They may also use different measurements and environmental control systems and employ different testing protocols. For these reasons, a standardized sweating manikin test procedure has been badly needed.

ASTM committee F23 on Protective Clothing is currently engaged in an effort to develop a standardized sweating manikin test procedure. By using a standard calibration garment, the ASTM method will enable available sweating manikin apparatus to produce equivalent characterization of the evaporative heat loss of clothing.

The ASTM sweating manikin test method will provide standardized means of calculating the total evaporative resistance of clothing ensembles. By adapting this method, and combining with an existing ASTM standard procedure for measuring clothing insulation using a dry manikin (ASTM F1291 [4]), a garment level equivalent of a total heat loss test is possible.

Studies have shown the potential value of using sweating manikins as tools for assessing the heat stress and comfort of clothing [38]. However, a systematic validation of manikin generated total heat loss data in conjunction with human physiological testing is yet to be conducted for firefighting/emergency responder protective gear.

Physiological Validation for Instrument Tests

The utility of sweating hot plate and sweating manikin test methods is limited by the lack of a sufficient number of well-qualified studies that establish correlations with the heat stress associated with wearing emergency responder protective gear. This situation is partly a result of the complexity of interrelated physical and physiological factors that combine to determine the impact of protective clothing on human heat stress response. Researchers have long recognized that the heat stress burden placed on a clothed individual is influenced by many interrelated environmental, physiological, and clothing material variables. These include ambient temperature, thermal radiation, relative humidity; wind velocity, heat and moisture transfer properties of clothing materials, clothing fit, stiffness, design, and tactile sensation. Some measured indictors are skin temperature, body core temperature, heart rate, metabolic rate, peripheral blood flow volume, sweat rate, and wetted area of skin. Psychological preference also plays a critical part. Perceived expectations, peer pressure and habit may determine the stress response regardless of measured physical and physiological parameters.

Because many variables can influence the specific translation between instrument readings and heat stress, performance criteria based on test measurements of the clothing material properties must be based on a comprehensive understanding of environmental and use conditions. Understanding these translations is an important part of an overall assessment of the gaps and limitations in laboratory tests in heat stress associated with protective clothing.

Survey of physiological studies on the heat stress in firefighter gear underscores the diversity of the physiological experimental designs that have been used. Investigations run the gamut from field trials to controlled laboratory studies. They have incorporated a wide range of different physiological stressing factors, used different environmental conditions, exercise regiments and clothing configurations [51, 56-57, 72-73, 92, 152, 157]. There is a lack of a common basis of comparison, and therefore point up a need to establish standard protocols for the physiological testing.

Many studies have been aimed at evaluating the heat stress impact of the breathability of the moistures barrier component used in firefighter turnouts. Recent studies have specifically focused on defining the correlation between the total heat loss (THL), measured using a sweating hot plate method and heat stress in firefighter turnouts [13, 96, 133]. These investigations have provided technical information to NFPA committees interested in establishing minimum performance requirements for heat stress. NFPA 1971 Standard for structural firefighting protective clothing and equipment currently requires a minimum sweating plate heat loss of 130w/m^2 for materials, used in turnout components. NFPA 1999 (EMS), NFPA 1971(Urban Search and Rescue) standards set the minimum acceptable total heat loss requirements at 450w/m^2.

In summary, setting minimum performance for emergency responder protective clothing based on sweating plate, or THL values, is difficult because of the complicating ensemble, environmental and use factors in these translations. Sweating manikin test methods provide opportunity to gain additional information since added clothing layers, as well as garment fit and design can be tested. In any case, more well-designed physiological studies are needed to quantify the translation between these tests (sweating plate and sweating manikin) and the heat stress of emergency responder ensembles. These correlations need to be developed for a broader range of environmental and use conditions. In this way, minimum performance levels for total heat loss can be established, for a wide variety of mission related conditions of emergency response.

Laboratory Tests for Clothing Comfort

Although physiological criteria are central to heat stress tolerance, the perceived comfort of protective clothing and acceptability of the clothing system must also be evaluated. One reason for this is that uncomfortable protective clothing might be removed or incorrectly worn, thus increasing the potential for hazardous environmental exposures and injury. Emergency response conditions that produce clothing related discomfort could occur long before disabling heat stress jeopardizes the responder. Discomfort responses caused by wearing protective clothing and associated with sensory perceptions of thermal and tactile sensations. Because human reaction to physical stimuli is subjective in nature, objective tests for these qualities have often proved to be challenging.

Comfort researchers recognize that clothing comfort has two main aspects that combine to create a subjective perception of satisfactory performance. These are thermo-physiological and sensorial comfort. The first relates to the way clothing buffers and dissipates metabolic heat and moisture. The latter relates to the interaction of the clothing with the senses of the wearer, particularly with the tactile response of the skin.

Thermophysiological comfort has two distinct phases. During normal wear, insensible perspiration is continuously generated by the body. Steady state heat and moisture vapor fluxes are thus created and must be gradually dissipated to maintain thermoregulation and a feeling of thermal comfort. The clothing becomes a part of the steady state thermoregulatory system. In transient wear conditions, characterized by intermittent pulses of moderate or heavy sweating caused by strenuous activity or climatic conditions, sensible perspiration and liquid sweat occur and must be rapidly managed by the clothing in order to maintain thermal regulation. The behavior of clothing in these two different domains may be predicted by certain measurable fabric properties, including thermal insulation and water vapor permeation resistance.

Measures of Steady State Vapor and Heat Transmission

Dry and evaporative heat transfer can be measured using sweating hot plates allowing calculation of various indices of thermal comfort including insulation (clo) and moisture vapor permeability.

Measurement of Pulsed Vapor and Heat Transmission

Measurement of fabric and microclimate response to pulsed moisture loads has been performed using the setup illustrated in Figure 10 [11].

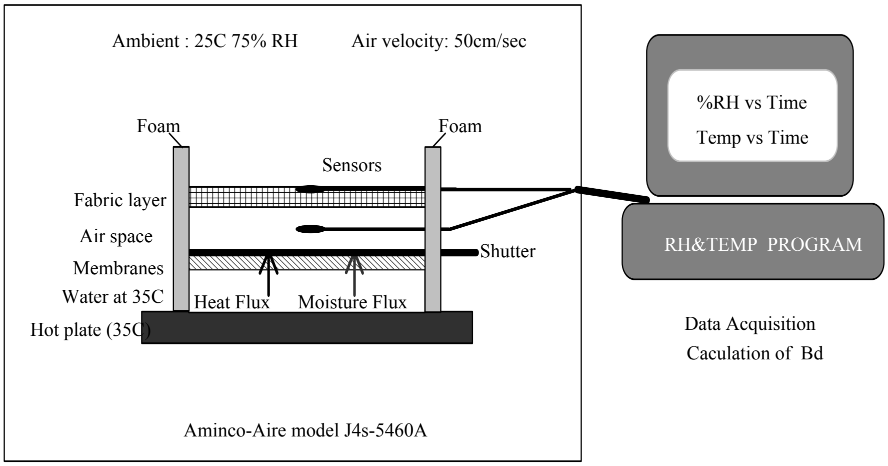


Figure 10. Dynamic Heat and Moisture Measurement System

A momentary vapor pressure gradient is created using a diffusion column with a shuttering device housed in an environmental chamber. Strategically placed high sensitivity/rapid response probes track the moisture and temperature pulse history in the microclimate and across the fabric layers. A consecutive series of moisture pulse can also be created and tracked, allowing simulation of a variety of expected end use scenarios.

Comfort Prediction Models

A theoretical model developed by Woo and Barker has been used to integrate the various measured comfort related physical properties of the fabrics into a prediction of human comfort limits for given climatic and metabolic work load conditions [22, 158]. The model is based on rates of heat loss and storage and their effect on conditions. The model is based on rates of heat loss and storage and their effect on body core temperature. Sensible and evaporative heat loss, as well as percent of skin area wetted by sweat, is considered. The model predicts the range of body activity within which an individual wearing a clothing system is thermophysiologically comfortable. Above these limits, heat stress is likely and below them hypothermia may occur.

The model is based on Woodcock's equation [159] for energy dissipation from the body. The total energy dissipated from a sweating human through clothing layers into an ambient environment, assuming no internal reactions (condensation, absorption or re-evaporation) within fabric components, can be expressed as:

Total Energy Dissipation – Dry heat transfer + Evaporative heat transfer, or

$$Q = Mn = (1/I)(T_s - T_a) + (1/R_v)(P_s - P_a)$$

Where: Q = total energy dissipation, w/m^2
Mn = net metabolic rate, w/sq m (usually, external work efficiency = 0 so $Q = Mn$)
I = thermal resistance of fabric to convective and radiant transfer, $m^{2\circ}C/w$
T_s = skin temperature, °C
T_a = ambient temperature, °C
R_v = water vapor resistance of fabric, m^2kPa/w
P_s = saturated vapor pressure at skin temperature, kPa
P_a = vapor pressure of ambient, kPa

It is useful to express fabric water vapor and thermal resistance as a ratio of those of free air. This ratio, known as the permeability index (i_m), ranges from 0 for impermeable to 1 for materials as permeable as free air. Also, the evaporative cooling term assumes the body is completely wetted by sweat but, in fact, beyond 20% sweat wetted area (SWA) and the terms of the more commonly used clo (I) units and introduce i_m and SWA and the relevant conversion constants, we obtain the formula for determining the upper and lower comfort limits:

$$(6.46/I)(T_s - T_a) < Mn < (6.46/I)[(T_s - T_a) + 3.3\, i_m(P_s - P_a)] < (6.46/I)[(T_s - T_a) + 16.5\, i_m(P_s - P_a)]$$

This model assumes that evaporative heat transfer in addition to dry heat transfer can extend the thermal comfort zone. The model contains three functional parameters. Those that are a function of fabric type (I, i_m), those that are a function of environmental conditions (T_a, P^a, air velocity) and a parameter that is a function of the amount of metabolic heat generated (Mn).

Resultant comfort ranges can be plotted for given environmental conditions. Since the plots represent the functional range of the fabric or fabric combinations in terms of allowable exertion, they are a key tool in the analytical determination of improved comfort performance.

Measurement of Liquid Moisture Absorption

The ability of a clothing material to transport moisture from sweat-wetted skin is crucial to wear comfort. Laboratory testing technologies have been developed to characterize the ability of a fabric to wick liquid moisture from sweating skin. One such test system is the Gravimetric Absorbency Testing System or GATS. The GATS procedure measures demand wettability. The test indicates the lateral wicking ability of the fabric, or the ability of the material to take up liquid in a direction perpendicular to the fabric surface. The GATS apparatus incorporates a special test cell and cover to assess absorption behavior in the presence of evaporation (Figure 11).

In this arrangement, liquid is drawn from a fluid reservoir by the capillary action of the fabric. The hydrostatic pressure of the fluid delivery system is adjusted by controlling the position of the sample platform. Liquid is delivered to the test material placed on a porous plate. Numerous pins, distributed over the area of the test surface uniformly restrain the test fabric. The amount (grams) of liquid siphoned from the reservoir is recorded as a function of time. These data are used to calculate absorption capacities and rates, and the percentage of moisture evaporated by the fabric. Applications of this device for protective clothing are discussed in reference [11, 18-19].

Measurement of Fabric Mechanical Properties

Fabric weight, and mechanical properties related to stiffness can be important determinants of comfort and ergonomics factors in protective clothing. Available laboratory tests for measuring these properties of clothing materials have not been widely used for protective clothing applications. The Kawabata Evaluation System (KES) is the most advanced laboratory testing system for measuring the surface and mechanical properties of fabrics. The KES instruments measure mechanical properties that correspond to the fundamental deformation of fabrics in manipulation that occurs in garment wear. Five different tests are performed using KES, including compression, bending, shear, tensile and surface properties, generating eighteen different mechanical characteristics.

Data on the mechanical properties of fabrics can be used to identify the contribution of tactile stiffness of material components to the flexibility and comfort of protective clothing designed for emergency responders.

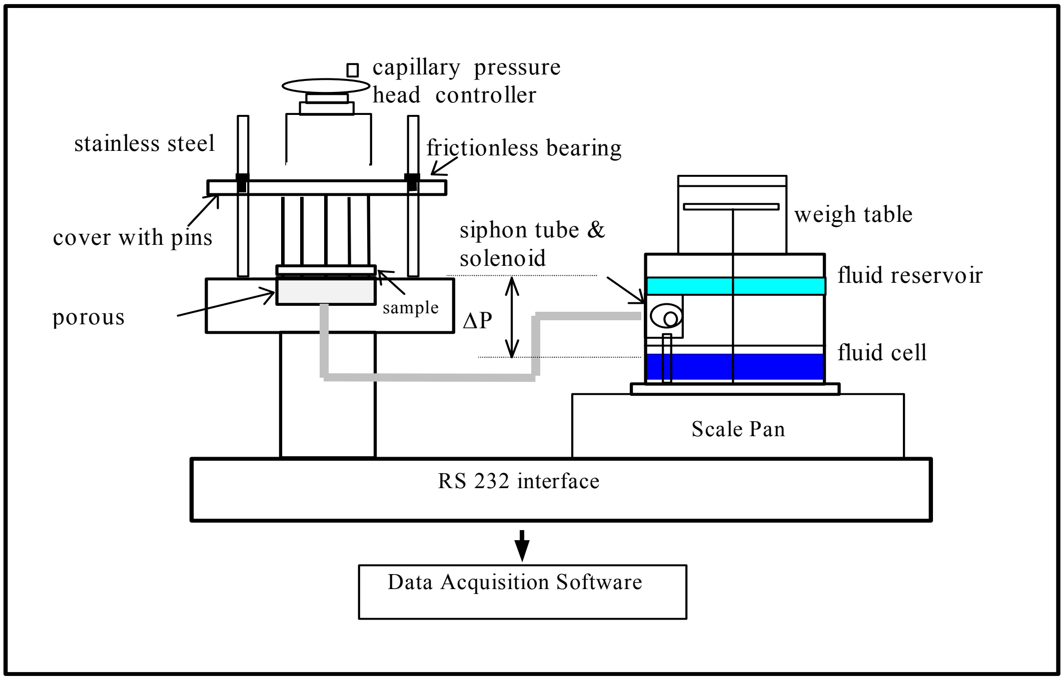


Figure 11. Gravimetric Absorbency Testing System (GATS)

Measurement of Ergonomic Factors

The ergonomic functionality of emergency responder ensembles is an important performance characteristic that requires evaluation. Evaluation of ergonomic performance involves characterizing the effects of ensembles and components on dexterity, range of motion, and the ease with which protective suits can be donned and doffed. Ergonomic tests have not been widely applied for PPE, partly because required protocols generally can involve elaborate human subject requirements and use subjective methods of assessment. ASTM F 1154 is an example of an available standardized test [5]. This test method describes standard practices for qualitatively evaluating the comfort, fit, function, and integrity of chemical protective ensembles. Exercise requirements in ASTM F 1154 are used in conjunction with liquid or gas tight integrity testing of chemical protective ensembles. Procedural options are also described in this method to evaluate the effect of protective ensemble on the ability of a test subject to perform routine work tasks. These protocols require adaption to be suitable for different types of protective ensembles and functionalities.

An additional need exists to develop improved test methods for evaluating the impact of protective gloves on manual dexterity. Glove hand function tests, such as those described in NFPA 1971 for gloves used by structural firefighters, typically assess the effect of the glove on a prescribed exercise, such as placing pegs into a peg board. Performance is evaluated based on comparison with a bare hand control [107]. Investigation of a new hand function tested for assessing multi-layer glove dexterity is discussed in reference [44].

Research Needs

Due to their primary function, protective materials often trap heat and moisture, creating a negative impact on comfort, health, safety, and efficiency. Traditional assessment techniques that rely on physiological protocols, while necessary for validation, are time consuming and costly. Currently, only a few studies support physiological testing capabilities. New materials and material combinations are continuously being introduced. Considerable merchandising in the protective clothing market has served to confuse the issue of heat stress impact on protective gear. There is a critical need for reliable instrumented test methods that can be used to evaluate the heat stress burden of protective clothing for emergency responders.

This review has identified the following specific areas where research is needed:

1. Development of an improved scientific validation for performance criteria bases on instrument test for heat stress.

Several testing technologies that have emerged are used to critically assess the heat stress potential of materials. Most significant of these are guarded sweating plates for small samples and sweating thermal manikins for complete ensembles. These methods provide consistent, reproducible measures. However, there is a continuing need to correlate and validate these measurement techniques with human physiological measures of heat stress tolerance for specific environments and protective clothing articles.

2. Development of an Improved Basis for Testing Standards Based on Sweating Manikins.

Much of the emphasis for firefighting and emergency responder clothing in standards is focused on material performance. This approach fails to consider garment design features as they impact thermal comfort. Manikin testing of full ensembles will provide better laboratory prediction of garment field performance and fit. It will also address the effects of design features, which currently are not evaluated. Correlation of bench level tests results with more representative full ensemble testing is needed to provide developers with the input needed to design better protective ensembles.

3. Development of an Application Basis for Laboratory Measurements of Non-Steady State Tests for Heat Stress and Comfort.

Steady-state heat transfer measurements made on sweating hot plates or sweating manikins do not provide information on dynamic changes in sweating environmental conditions. Laboratory testing procedures are available which could be applied to measure these phenomena.

4. Development of an Application basis for Laboratory Procedures for Measuring Sensorial Comfort.

Perceived comfort has been largely overlooked in testing standards for firefighter protective clothing. Laboratory test methods measuring for material properties associated with sensorial comfort including predictive tests for sweat absorption and tactile factors such as fabric stiffness and softness. A qualified basis is needed for applying these test methods to materials used in emergency responder protective clothing.

5. Development of a set of practical guidelines that would inform emergency responder how their selection of a protective ensemble would impact them to function in specific situations.

The impact of protective ensembles on heat stress tolerance is, ultimately, determined by a complex set of variables involving, not only elements of the protective clothing system, but use variables controlled by environmental and other factors. Although integrating models have been developed, more research is needed to advance the basis upon which physical parameters are used to predict heat stress tolerance.

Test methods, and associated performance criteria, developed through research in these areas will advance the development of protective ensembles for emergency responders that will provide for reduced heat stress, as well as improved comfort and ergonomic functionality. Research is needed to develop and adopt test methods for evaluating the effect of protective ensembles and components on dexterity, range of motion, and ease of donning and doffing.

CHAPTER V

IN-USE DURABILITY AND SERVICE LIFE

The development of advanced ensembles for emergency responders requires protocols for testing and verifying that these systems provide primary protection against environmental threats, while maintaining adequate levels of functional performance. Modern, multi layer protective suits may provide excellent initial protection and thermal properties, but their protective performance can deteriorate in exposure to the harsh physical and environmental factors faced in emergency responders. Emergency responders may expose protective garments to heat, soiling, chemical, UV radiation, abrasion and compression, and saturation with sweat and water. Cleaning processes can further expose garments to laundry chemicals, to saturation with hot water, and to drying cycles. In these conditions, for example, the moisture or chemical/biological barrier may degrade long before wear is apparent to the outer shell fabric of the garment.

NFPA 1851, Standard On Selection, Care and Maintenance Of Structural Firefighting Protective Ensembles [105] is written to enable users to inspect, maintain and care for gear used in structural firefighting operations. This standard provides guidelines for routine inspection of soiling, contaminants, and physical damage to turnouts and other elements of the firefighter ensemble. The standard also makes recommendations on testing for the effects of cleaning agents and procedures on retention key performance properties in the outer shell, moisture barrier, moisture barrier seams, and thermal liner components. Manufacturers trade organizations, such as the Fire and Emergency Manufacturers and Services Association (FEMSA) also supply users information guides that contain general recommendations on inspection, washing, storage, and retirement procedures for firefighter turnouts [47].

While NFPA standards and manufacturers' information provide general guidelines on evaluating fire service use, need exists for test methods that can predict the service life performance of materials used in firefighter protective clothing. Comparatively little research has been conducted on this subject, probably because of the multitude of ensemble and exposure conditions that combine to degrade the performance in firefighter gear [93, 122-123, 145].

The expected service life durability of protective materials can be estimated using protocols that measure the effects of accelerated exposures and use conditions on performance properties. Aside for testing materials after repeated washing cycles, requirements for performance testing following preconditioning to simulate use have not been fully incorporated into NFPA standards for firefighter garments.

Researchers have recognized the challenges involved in establishing guidelines for the retirement of firefighters protective clothing, including proper characterization of the conditions of use and the effects on protective performance. They point out that the development of systematic retirement guidelines requires laboratory testing of garments subjected to controlled conditions as well as testing of garments taken from the field [147].

Other issues that have emerged related to the degradation of protective performance as a result of exposure and use, include: the loss of mechanical integrity in the outer shell fabrics in firefighter turnouts due to heat exposures; deterioration in the moisture barrier component in turnouts as a result of UV or heat exposure, and the ruggedness of components used in urban search and rescue ensembles.

Strength Retention in Thermally Degraded Shell Fabrics

Degradation of the mechanical strength of shell materials, the outer protective layer of a firefighter turnout system, may contribute to burns received by firefighters. During flashover exposure, the mechanical integrity of some shell materials can degrade to the point where, under normal flexing of the system due to the motion of the firefighter, the material can break open and expose the underlying moisture barrier and the thermal liner to flames. Failure of a thermal protective fabric to maintain structural integrity may expose the firefighter to the heat hazard and resulting heat transfer. Therefore, one test of a heat resistant protective material is a measure of its ability to provide thermal insulation when exposed simultaneously to intense heat and to mechanical stress and strain.

Current TPP tests provide valuable information that is directly related to the end-use performance of thermal protective garments. However, these methods assess heat transfer while the fabric is in a static and unstressed state. They do not evaluate thermal performance under conditions simulating body movement generated by a firefighter escaping from a fire. The normal reaction of a firefighter in a fire accident is to try to escape the heat hazard by running away from the fire source. Even if the firefighter already suffers some degree of burn injury, it is unlikely that external burns will affect internal body organs in short exposures. Therefore, a scenario is likely where the firefighter will remain conscious and active at least during the period that immediately follows the fire accident. The active firefighter's movements impose mechanical strains on clothing fabrics, particularly at the knee, upper leg, arm and back. In these areas, the fabrics are subjected to mechanical tensile and bending stresses.

Although these phenomena have been studied in single layer fabrics [20, 23, 54], there is currently no standard test method or performance specification to assess the retention of strength of turnout materials in exposures to fire conditions.

Effects of Ultraviolet Radiation and Heat Exposure

In use exposures of turnout gear to heat, UV radiation, chemicals and to hot water, laundry chemical and to drying in laundering may affect the liquid resistance and moisture vapor permeability of moisture barriers. This is a significant concern to the firefighter, since the moisture barrier component is required to provide primary liquid resistance, and the breathability of the turnout composite. Recent attention has been focused on developing test protocols to evaluate the water penetration resistance of moisture barriers following exposures to UV radiation. The hydrostatic resistance of the moisture barrier component is measured following accelerated UV exposure in a Xenon arc light apparatus.

UV exposure preconditioning protocols currently being considered by NFPA 1971 represent a positive development. However, research is needed to develop testing procedures that will provide more accurate and comprehensive assessment of use conditions on ensemble barrier materials. Development of systematic protocols requires a better fundamental understanding of the mechanisms of degradation associated with elevated heat, chemicals and UV light and laundering. This understanding will guide the development of preconditioning methods that will simulate the combined effects of field exposures, prolonged storage and laundering.

Evaluating the Ruggedness of USAR Protective Ensembles

As identified in recent emergency response events related to the September 11 attacks, first responders found that their clothing, gloves, and footwear, quickly deteriorated with long-term rescue efforts associated with these events. Even though intended for structural fire fighting, both gloves and footwear quickly deteriorated and required frequent replacement. Improved laboratory tests are needed to reliably predict protection from cuts, abrasion and puncture in extended use. These performance requirements, physical protection and durability testing need to be addressed with focused research efforts. A battery of both current puncture and abrasive tests and development of new tests will be required to address the protective performance to physical hazards and durability of USAR garments.

CHAPTER VI

MODELS for PREDICTING the PERFORMANCE of PROTECTIVE CLOTHING

The utility of data generated by laboratory tests would be greatly increased by the availability of computer based models that can analyze and interpret results in the light of material properties and garment design. These analytical models could serve as tools to assist the development of new materials. They could forecast the effects of design options on the resulting protection and comfort on ensembles for emergency response.

Development of performance predicting models will require significant advances in our present understanding of heat and mass transfer processes in protective clothing systems and how these processes influence thermal and chemical/biological protection. Also needed is a basic understanding of how different materials and garment elements combine to determine the balance between protective and heat stress. For example, predicting garment performance in preventing burn injuries requires a capability to model heat transfer from heat sources to the protective clothing, through clothing interfacial air gaps, and finally, to the skin. Promising advances have been recently made in the state-of-the-art of heat transfer modeling for the protective garments [130, 133, 145]. Nevertheless, work is needed to develop these models to the stage that they can be reliably used to predict thermal protective performance of multi-layer protective ensembles. Test methods are needed to generate a database on the effects of intense heat exposure on fabric thermophysical properties. Current models for thermal protective garments are also limited by an incomplete fundamental understanding of moisture on protection.

Other models are needed to predict the effects of materials and garment design elements on thermal and chemical/biological protection as well as factors contributing to the heat stress of protective clothing.

CHAPTER VII

SUMMARY of RESEARCH NEEDS for DEVELOPMENT of TEST METHODS and PERFORMANCE CRITERIA

Research is needed to develop test methods and performance criteria aimed at simultaneously maximizing the three competing performance areas for emergency responder protective clothing and equipment - protection, functionality and comfort. Identified gaps and limitations in available methodologies and performance criteria provide specific basis for the following research projects for test methods development:

1. Whole Garment Tests and Performance Criteria for Protective Ensembles

Development and/ or adaptation of instrumented manikin test procedures for evaluating resistance to thermal, chemical/ biological threats and to assess and predict ensemble heat stress based on ensemble properties has been identified as a priority need. Well-qualified physiological studies are needed to establish correlations with instrument tests and the heat stress associated with wearing emergency responder protective gear.

2. Simulant Tests for Chemical/ Biological Agents

Research is needed to develop bench and full-scale ensemble tests for inward leakage of gaseous, vapor, and liquid agents through respirators and clothing. This may require the development of surrogate chemicals to model the effect of toxic agents on barrier films, fabrics, and closures. Test methods are needed to evaluate the effect of the surrogates on the strength and durability of garments, and the ability of the surrogate to be transported through the barrier materials and closures.

3. Tests for Biological Threats from Aerosols and/ or Particulates

Research is needed to establish test methods for evaluating complete protective clothing and respirators against airborne bioterrorism particulates. The recent events associated with anthrax demonstrate the difficulties of applying current response protective technology to specific bioterrorism events. Tests are needed to evaluate both closures and whole clothing items to permit an assessment of seams, closures, and interfaces that are not evaluated by bench top material tests. Tests to evaluate particle penetration through filters and absorbents used for respirator protection in addition to the respirator to garment interface also need to be developed.

4. Simulant Tests for Toxic Agents for SCBA Gear

Research is needed to identify and evaluate appropriate agents to simulate toxic agents with respect to chemical physical properties and barrier (permeation) properties. The resistance of SCBA components to attack by simulated toxic agents needs to be compared to results of whole SCBA laboratory with actual toxic agents. The simulants could also be used to evaluate impact of chemical agent sorption on fit and durability.

5. Tests for Thermal Protection in Sub-Flashover Environments

Research is needed to develop or adapt laboratory test methods and performance criteria for evaluating the thermal protective performance of firefighter clothing, including moisture effects, in sub-flashover heat exposures. Test method development may require the development of new bench scale radiant heat sources as well as developing or adapting thermal sensors and burn algorithms for use in tests that involve prolonged exposures to low level radiant heat.

6. Tests for Ergonomic Function and Comfort

Research is needed to develop test methods and performance requirements for evaluating properties associated with the sensorial comfort and dexterity, stiffness, donning and doffing of first responder ensembles and components. Performance criteria specific to the ergonomic and comfort performance of first responder gear need to be developed in concert with testing protocols.

7. Tests for Ruggedness of USAR Protective Ensembles

Research is needed to develop and/ or identify a battery of physical hazard and durability tests that can be applied to clothing items, gloves, and footwear used in technical rescue operations.
Puncture and cut resistance could be a focus, exploring both current and new test procedures. Durability can be evaluated by abrasion testing using a variety of surface exposures, through the use of microscopic and gross surface characterization techniques, and by comparing to field data in the presence of a variety of working surfaces. The impact of wetting and extended sunlight exposure for the materials on durability needs to be considered.

8. Tests to Predict In-Use Performance and Service Life

Research is needed to develop test methods that will predict the effects of use history, cleaning/ care, and UV exposure on the protective performance of turnout gear. These test methods and performance criteria would provide a basis for the care, storage and maintenance standards for firefighter ensembles. Research is also needed to develop protocols and performance criteria evaluating the effects of thermal degradation of outer shell materials on the thermal protective performance of turnout systems.

9. Development of Computer Based Predictive Models

Research is needed to develop analytical models that can be used to predict the effects of materials and garment design elements on thermal and chemical/ biological protection as well as factors contributing to the heat stress of protective clothing.

Test methods, and associated performance criteria, developed through research in these areas will advance the development of new protective ensemble technologies. They would also provide for improved performance standards for protective clothing and equipment used in emergency response.

ACKNOWLEDGEMENT

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APPENDIX A

SUMMARY of KEY TEST METHODS and REQUIREMENTS for EVALUATING FIREFIGHTER PROTECTIVE CLOTHING and EQUIPMENT

Note: Appendix A contains a detailed summarized review of test methods in NFPA 1971, Standard on Protective Ensembles for Structural Fire Fighting, 2000 Edition, NFPA 1951, Standard on Protective Ensembles for USAR Operations, 2001 Edition, and NFPA 1994, Standard on Protective Ensembles for Chemical/Biological Terrorism Incidents, 2001 Edition.

Table A1. NFPA 1971 Test Methods and Requirements for Measuring Flame Resistance. [1,2]

Ensemble Component Tested	Test Method or Procedure	Performance Criteria	Comments
Garment materials (outer shell, moisture barrier, thermal barrier, and other materials used in garment)	FTM 191A,5903.1: Specimen edge vertically suspended 0.75 inch above 1.5 inch flame for 12 seconds.	After flame time ≤ 2 seconds; char length ≤ 4 inches; no melting or dripping.	Vertical flame test on fabric strips; measures continued flaming and thermal damage to test sample.
Gloves (composite)	FTM 191A, 5905,1 (modified): specimen folded in L shape with fold suspended above 1.5 inch flame for 12 seconds.	Afterflame time ≤ 2 seconds; char length ≤ 4 inches; specimen consumption ≤ 5% (by weight); no melting or dripping.	2 x 6 inch glove composite exposed with specimen's normal outer surface exposed to flame.
Footwear	FTM 191A, 5905.1 (modified): Whole boot suspended 0.75 inch vertically over 1.5 inch flame.	Afterflame time ≤ 2 seconds at any area; no melting or dripping; no burn-through.	Flame directed only to specific areas of whole footwear.
Helmet and faceshield	Test Procedure A – helmet tested with face shield in position; 1-1.5 in flame applied to outer edge of the helmet, at the front, sides, and run for 15 seconds. Test Procedure B- helmet tested with face shield in lowered position; 1-1.5 inch flame applied at 45° for bottom edge of face shield for 15 seconds.	No visible flame or glow 5 seconds after removal from flame.	Provides limited simulation of helmet/faceshield configurations and flame exposures.
Hood and wristlet materials	FTM 191A, 5903.1: Specimen edge vertically suspended 0.75 inch above 1.5 inch flame for 12 seconds.	Afterflame time ≤ 2 seconds; Char length ≤ 4 inches. No melting or dripping.	Same procedures as applied to garment materials.

[1] Specific conditioning procedures are required for some components; garment materials, glove composites, hood materials and wristlet materials are tested before and after 5 cycles of laundering.

[2] Tabulated information is abstracted from NFPA 1971. This standard should be consulted for detailed specification of test methods, performance criteria, and preconditioning protocols.

Table A2. NFPA 1971 Test Methods and Requirements for Measuring Convective Heat Resistance. [1, 2]

Ensemble Component Tested	Test Method or Procedure	Performance Criteria	Comments
Garment materials (outer shell, moisture barrier, thermal barrier, and other materials used in garment , including trim, moisture barrier seams) **Wristlet material** **Helmet ear cover and chin strap materials**	Specimens are supported or suspended in a forced circulating air oven at 260º (500ºF) for 5 minutes.	No melting, separation, ignition or dripping (textiles or other materials); no charring (outer shell only); no ignition or dripping (moisture barrier seams). Thermal shrinkage ≤10% for outer shell, moisture barrier, thermal barrier, and winter liner.	Provides limited simulation of heat exposures under static conditions; does not assess functional performance or intrinsic thermal stability.
Gloves **Glove innermost lining material**	Same as for garment materials, except whole gloves filled with vermiculite are tested; innermost material of glove composite also tested.	No separation, melting, or dripping; thermal shrinkage ≤8%; gloves are donnable and flexible (gloves); no melting, separation or ignition (innermost layer).	Provides limited simulation of heat exposures; test includes functional requirement of gloves; lining material not evaluated for thermal shrinkage.
Footwear	Same as garment materials, except men size 9 boot, filled with vermiculite is tested; boots are emptied, flexed and tested for water penetration.	No separation, melting or dripping, all components remain in place and are functional; no water penetration following flexing.	Provides limited simulation of heat exposures; test includes assessment of functional performance and integrity following heat exposure.
Helmet and faceshield	Same as garment, except complete helmet tested is tested nonconductive test headform with ear covers deployed.	No new contact with head form; no separation, melting or dripping, no ignition of whole helmet; chin strap closure remains functional.	Provides limited simulation of heat exposures.
Hoods	Same as garment, except whole hoods are tested on non-conductive headform.	No separation, melting or ignition; thermal shrinkage ≤8%	Provides limited simulation of heat exposures.

[1] Specific conditioning procedures are required for some components; garment materials, gloves, helmet ear cover/chins strap materials, hoods and wristlet materials are tested before and after 5 cycles of laundering.

[2] Tabulated information is abstracted from NFPA 1971. This standard should be consulted for detailed specification of test methods, performance requirements, and preconditioning protocols.

Table A3. NFPA 1971 Test Methods and Requirements for Measuring Conductive Heat Resistance. [1, 2]

Ensemble Component Tested	Test Method or Procedure	Performance Criteria	Comments
Gloves (composite) **Footwear (upper)**	ASTM F1060: Specimens of glove body placed on a hot plate set at 280°C (536°F). Stoll criteria is used to predict time to pain and to second degree burn.	Predicted time to 2nd degree burn < 10 seconds; Predicted time to pain < 6 seconds.	Sample compressed at 0.5 psi. Wet and dry samples of gloves are tested.
Footwear (sole)	Complete boot tested in contact with plate heated to 500°C (932°F). Thermocouple fixed to insole measured after 30 seconds.	Insole temperature ≤111°F.	Thermal protective index based on thermocouple temperature. Provides limited prediction of burn protection.
Garment composites (shoulder and knee areas only).	ASTM F1060 (modified): Measures conductive and compressive heat resistance (CCHR). Shoulder specimens tested at 13.8 kpa (2 psi); knee specimens tested at 55.2 kPa (8 psi).	Time to transmit sufficient heat through test sample to produce a 24°C (46°F) temperature rise in thermal sensor.	Wet and dry samples measured. Wet conditioning involves wetting of thermal barrier portion of composite only based on barrier ability to pick up water; water weight gain varies with type of thermal barrier tested.
Thread (garments, helmets, gloves, footwear)	FMS 191A,1534: Small piece of thread is subjected to Soxhlet extraction and then placed on heated microstage with observation of condition.	Melting temperature ≤260°C (500°F)	Method is intended to determine thermal stability of thread under high heat conditions; may not relate to actual performance of seam.

[1] Specific conditioning procedures are required for some components; gloves are tested before and after 5 cycles of laundering and following wet preconditioning; garment shoulder and knee composites are tested after 5 cycles of laundering under both dry and wet conditions.

[2] Tabulated information is abstracted from NFPA 1971. This standard should be consulted for detailed specification of test methods, performance requirements, and preconditioning protocols.

Table A4. NFPA 1971 Test Methods and Requirements for Measuring Radiant Heat Resistance and Thermal Protective Performance. [1, 2]

Ensemble Component Tested	Test Method or Procedure	Performance Criteria	Comments
Garment composite **Hoods and wristlets**	TPP tester used to expose samples to radiant/ convective heat at 2.0 cal/cm^{2}sec. Stoll criteria used to predict time to 2nd degree burn injury.	TPP rating $\geq$ 35 (coat and trousers); TPP $\geq$ 20 (hoods and wristlets).	Predicts thermal protective performance in emergency (flashover) environments. Static test; does not measure flammability or effects of thermal degradation.
Gloves (composite)	Same as garment composite.	Same as garment composite.	Provides limited simulation of radiant heat exposures for gloves.
Footwear	Complete boot exposed to radiant panel set to produce 1.0 w/m^2 heat flux. Temperature of thermocouple affixed to inside surface of lining of boot is measured at 1 minute.	Lining temperature ≤111°F.	Specimen configuration is an issue. Predictive index based on thermocouple; provides limited prediction of burn protection.
Helmet	Top of helmet is sequentially exposed to combination of heat from radiant panel (1.0 w/m^2) and 1000 btu/ft^2 methane gas Bunsen burner flame.	Afterflame time < 5.0 seconds.	Specimen configuration is an issue. Provides indirect measure of thermal protective insulation.

[1] Specific conditioning procedures are required for some components; garment composite, hood material, wristlet material, and glove composites are tested before and after 5 cycles of laundering.

[2] Tabulated information is abstracted from NFPA 1971. This standard should be consulted for detailed specification of test methods, performance requirements, and preconditioning protocols.

Table A5. NFPA 1971 Test Methods and Requirements for Measuring Water Absorption, Water Penetration, Liquid Penetration, and Viral Resistance. [1, 2]

Ensemble Component Tested	Test Method or Procedure	Performance Criteria	Comments
Garment	ASTM F1359: garment is placed on manikin over liquid absorptive garment and exposed surfactant treated water spray (35 dynes/cm) of 20 minutes in 4 different orientations.	No evidence of liquid or liquid absorption; the garment and the interior of the manikin.	Only whole garment test in NFPA 1971 Standard. Report interpretation based on subjective criteria.
Garment materials (moisture barrier)	FTMS 191A, 5512: Hydrostatic test with pressure ramped to at least 25 psi	Water penetration resistance ≥ 25 psi	High pressure hydrostatic test assesses coating or lamination strength.
Moisture barrier seams for garment, gloves, and footwear	ASTM F903, Procedure C: Seam samples exposed to fireground chemicals after conditioning for 1 hour, with one minute at 13.8 kPa (2 psi); penetration visually observed	Evidence of liquid in one hour, constitutes failure in test.	Test liquids are AFFF, battery acid, hydraulic fluid, surrogate gasoline fuel C, and swimming pool chlorinated chemical; Test samples undergo various preconditioning procedures prior to testing, including washing and exposure to convective heat.
Moisture barrier seams for garment, gloves, footwear	ASTM F1671: Seams samples exposed to biochallenge solution after conditioning for 1 hour, with one minute at 13.8 kPa (2 psi); penetration based on bioassay method involving rinse of sample interior surface following exposures	Evidence of viral penetration, in one hour, constitutes failure in test.	Phi-X-174 Bacteriophage is used as surrogate for blood borne pathogen. As with liquid penetration, samples undergo various preconditioning procedures prior to testing, including washing and exposure to convective heat.

[1] Specific conditioning procedures are required; overall garments are tested after 5 cycles of laundering; moisture barriers are tested for water penetration before and after 5 cycles of laundering, and after a 10 minute 140°C (285°F) oven heat exposure; moisture barrier seams are tested for liquid and viral penetration testing following 2 series of heat exposures at 140°C (285°F) and 5 cycles of laundering.

[2] Tabulated information is abstracted from NFPA 1971. This standard should be consulted for detailed specification of test methods, performance requirements, and preconditioning protocols.

Table A6. NFPA 1971 Test Methods and Requirements for Measuring Total Heat Loss and Element Function. [1, 2]

Ensemble Component Tested	Test Method or Procedure	Performance Criteria	Comments
Garment Composite	ASTM F1868, Procedure C: Composite materials are laid flat on sweating hot plate with measurement of thermal and evaporative resistances.	THL ≥ 130 w/m^2.	Measures breathability of flat garment composite samples.
Gloves	Liner Retention Test: Assesses liner retention after multiple launderings of whole gloves.	Glove donning time ≤ baseline time plus 20 seconds.	Evaluates effect of gloves on hand functions - donning, dexterity, and grip.
	Dexterity Test: Time for test subjects to place pegs in pegboard is measured with and without gloves.	Dexterity time with gloves ≤ 300 percent greater than barehanded value.	
	Grip Test: Weight that can be lifted by test subjected using halyard and pulley Is measured with and without gloves.	Weight pulling capacity with gloves ≥ 90 percent bare handed value.	
Footwear	Ladder shank bend test: deflection of ladder shank is measured under 182 kg (400 lb) force.	Deflection ≤ 6 mm (0.25 in.).	Intended to keep footwear sole stiff when climbing ladders or walking on uneven surfaces.

[1] Specific conditioning procedures are required for some components; in dexterity test, gloves are evaluated after 5 cycles of laundering; in grip test, gloves are evaluated before and after 5 cycles of laundering, in both dry and wet conditions.

[2] Tabulated information is abstracted from NFPA 1971. This standard should be consulted for detailed specification of test methods, performance requirements, and preconditioning protocols.

Table A7. NFPA 1971 Test Methods and Requirements for Measuring Physical Properties.[1, 2]

Ensemble Component Tested	**Test Method or Procedure**	**Performance Criteria**	Comments
Garment materials (outer shell, moisture barrier, thermal barrier, and winter liner)	ASTM D5733: Tear strength (trap tear method)	Tear strength ≥100 N (22 lb$_f$) (outer shell and collar linings), ≥22 N (5 lb$_f$) (moisture barriers, thermal barriers, and winter liners.	Tear strength of fabric materials is determined by fiber type, yarn, fabric weight.
Garment material (outer shell)	ASTM D5034: Breaking strength	Breaking strength ≥623 N (140 lb$_f$)	Grab strength type method is used.
Garment material seams (major A, major B, minor seams)	ASTM D1683: Seam strength (for woven fabrics) ASTM D3940 Burst strength (for knit and stretch woven fabrics)	Seam strength ≥667 N (150 lb$_f$) (Major A seams); ≥334 N (75 lb$_f$) (Major B seams); and ≥180 N (40 lb$_f$) (Minor seams); Burst strength ≥180 N (140 lb$_f$).	Seam requirements are based on their location in the garment, their function, and the type of materials used.
Gloves (composite)	ASTM F1790: Cut resistance	Cut distance >25mm (1 in.) at 400 g load.	Measures distance of blade travel over material before cut through.
	ASTM F1342: Puncture Resistance	Puncture force >4.0 kg (8.5 lb).	Measures force of nail like probe to puncture composite.
Gloves (gauntlet or wristlet)	ASTM D3787: Bursting strength (ball burst method)	Burst strength ≥2.3 kg (50.6 lb).	Measures force for 1-inch ball to push through fabric.
	ASTM F1790: Cut resistance	Cut distance ≥25 mm (1-in.) at 400 g load.	Same as glove composite.
Footwear (upper)	ASTM F1342: Puncture resistance:	Puncture force >6 kg (13.2 lb).	Same as glove composite.
	ASTM F1790: Cut resistance	Cut distance ≥25 mm (1-in.) at 800 g.	Same as glove composite.
Footwear (sole)	ANSI Z41: Puncture resistance:	Puncture force ≥1211.6 N (272 lb$_f$).	Same requirement as industrial footwear.
	ASTM F489: Static coefficient of fiction by James Machine	Slip resistance (static coefficient) ≥0.75 (dry).	Applied to both sole and heel materials (not sole samples).
	ASTM D1630: Footwear abrasion	Abrasion Index >100.	Compares mass removed versus pristine sample.

[1] Specific conditioning procedures are required; garment breaking strength measured after 10 laundering cycles; garment seam strength and glove puncture resistance is tested after 5 cycles of laundering.

[2] Tabulated information is abstracted from NFPA 1971. This standard should be consulted for detailed specification of test methods, performance requirements, and preconditioning protocols.

Table A7. NFPA 1971 Test Methods and Requirements for Measuring Physical Properties.[1,2] (continued)

Ensemble Component Tested	**Test Method or Procedure**	**Performance Criteria**	Comments
Footwear (toe)	ANSI Z41: Impact/compression resistance	Impact resistance ≥ 101.7 J (75 ft-lb); compression resistance ≥13 mm at 11,121 N (2500 lb_f)	Same requirement as industrial footwear.
Helmets	Impact resistance test (force)	Transmission of force ≤3780 N (850 lb_f)	Measures force transmission through helmet when struck by anvil
	Impact resistance test (acceleration)	Acceleration ≤1471.5 m/s^2 (4830 ft/s^2) (helmet top); ≤2943 m/s^2 (9660 ft/s^2) (helmet front, sides, back)	Similar to force measurement but looks at helmet acceleration
	Physical penetration test	No electrical contact	Specific weighted, blunt anvil dropped on helmet
	Retention system test	No breakage of retention system and slip/stretch ≤20 mm (13/16 in.)	Force to pull the retention system is measured
	Shell retention test	No separation of suspension from helmet	Measures force to break for chinstrap of helmet
Helmet suspension systems	Suspension system retention test	No separation of suspension from helmet	Force applied in pulling suspension system from helmet
Faceshield and goggles	Lens impact resistance test	No contact of projectile or fragments with eyes of headform	Two tests measure resistance of lens material to impact to high mass object and high velocity object
	Lens abrasion test	Change in haze ≤25%	Measures changes in lens haze following abrasion
Hoods and wristlets	ASTM D3787: Burst strength (ball burst method)	Burst strength (hood) >225N (51 lb_f)	See glove wristlet
	ASTM D3940: Burst strength for seam	Seam strength ≥181N (41 lb_f)	Same as garment

[1] Specific conditioning procedures are required for some components; helmets/faceshield preconditions include low temperature, convective heat, radiant heat, and wet conditioning; hood and wristlet materials are tested after 5 cycles of laundering.

[2] Tabulated information is abstracted from NFPA 1971. This standard should be consulted for detailed specification of test methods, performance requirements, and preconditioning protocols.

Table A8. NFPA 1971 Test Methods and Requirements for Measuring Miscellaneous Properties.[1]

Ensemble Component Tested	**Test Method or Procedure**	**Performance Criteria**	Comments
Garment materials (outer shell, liquid barrier, and liners)	AATCC 135: Cleaning shrinkage; measured after 10 cycles of laundering.	Shrinkage ≤5%.	Set acceptable shrinkage as 1 size difference.
Garment trim **Helmet trim**	Retroreflectivity and fluorescence test: Special device is used to measure nighttime brightness of trim new, following heat exposure, and during rainfall; assessment of fluorescence based on observation	Coefficient of retroreflectivity ≥ 100 cd/lux/m^2 (cd/fc/ft^2); trim designated as fluorescent.	Fluorescence is not measured, only observed
Product labels (garments, gloves, footwear, helmets, and hoods)	Label legibility test: Label examined for legibility following washing, heat exposure, and light abrasion	Labels remain legible.	Interpretation of pass/fail is subjective; helmets only tested after heat exposure; footwear after heat exposure/abrasion.
Helmets	Electrical insulation test (helmets): evaluates helmets against 50-Hz AC.	Current leakage ≤ 3 mA.	Current flow through helmet in two procedures
Footwear	ASTM F1116: 14,000 V exposure with conductive metal shot inside boots	Current leakage ≤ 5 mA.	Different requirement applied to footwear as compared to helmets
Hardware (garments, gloves, footwear, helmets)	ASTM B117: corrosion resistance measured with 5% salt spray for 20 hours	Inherently resistant metals must show no more than surface-type corrosion or oxidation; ferrous must show no corrosion of base metal; hardware must remain functional.	Interpretation of pass/fail is subjective

[1] Tabulated information is abstracted from NFPA 1971. This standard should be consulted for detailed specification of test methods, performance requirements, and preconditioning protocols.

Table A9. NFPA 1951 Test Methods and Requirements for Measuring Flame Resistance. [1,2]

Ensemble Component Tested	Test Method or Procedure	Performance Criteria	Comments
Garment materials (textile fabrics, linings, collar linings, trim, lettering, and other materials used in garment)	ASTM D6413: Specimen edge vertically suspended 0.75 inch above 1.5 inch flame for 12 seconds.	After flame time ≤ 2 seconds; char length ≤ 4 inches; no melting or dripping.	Vertical flame test on fabric strips; measures continued flaming and thermal damage to test sample.
Gloves (composite)	FTM 191A, 5905,1 (modified): specimen folded in L shape with fold suspended above 1.5 inch flame for 12 seconds.	Afterflame time ≤ 2 seconds; char length ≤ 4 inches; no melting or dripping.	2 x 6 inch glove composite exposed with specimen's normal outer surface exposed to flame.
Footwear	FTM 191A, 5905.1 (modified): Whole boot suspended 0.75 inch vertically over 1.5 inch flame.	Afterflame time ≤ 2 seconds at any area; no melting or dripping.	Flame directed only to specific areas of whole footwear.
Helmet	Test Procedure A – helmet tested with face shield in position; 1-1.5 in flame applied to outer edge of the helmet, at the front, sides, and run for 15 seconds.	Afterflame time ≤ 5 seconds.	Provides limited simulation of helmet and flame exposures.
Eye and face protection device	Test Procedure B- helmet tested with face shield in lowered position; 1-1.5 inch flame applied at 45º for bottom edge of face shield for 15 seconds	Afterflame time ≤ 5 seconds.	Provides limited simulation of eye/face protection device and flame exposures.

[1] Specific conditioning procedures are required for some components; garment materials and glove composites are tested before and after 10 cycles of laundering.

[2] Tabulated information is abstracted from NFPA 1952. This standard should be consulted for detailed specification of test methods, performance criteria, and preconditioning protocols.

Table A10. NFPA 1951 Test Methods and Requirements for Measuring Convective Heat Resistance. [1, 2]

Ensemble Component Tested	Test Method or Procedure	Performance Criteria	Comments
Garment materials (textile fabrics, linings, collar linings, trim, lettering, and other materials used in garment)	Specimens are supported or suspended in a forced circulating air oven at 260º (500ºF) for 5 minutes.	No melting, separation, ignition, or ignition (textiles or other materials). Thermal shrinkage ≤10% for outer shell, moisture barrier, thermal barrier, and winter liner.	Provides limited simulation of heat exposures under static conditions; does not assess functional performance or intrinsic thermal stability.
Gloves	Same as for garment materials, except whole gloves filled with vermiculite are tested.	No separation, melting, or dripping; thermal shrinkage ≤10%.	Provides limited simulation of heat exposures; no functional requirement for gloves; lining material not evaluated.
Footwear	Same as garment materials, except men size 9 boot, filled with vermiculite is tested.	No separation, melting or dripping, all hardware (except laces) remains functional.	Provides limited simulation of heat exposures.
Helmet	Same as garment, except complete helmet tested is tested non-conductive test headform.	Deformation of brim and peak ≤25%; hardware remains functional.	Provides limited simulation of heat exposures.
Eye and face protection device	Same as garment materials except eye and face protection device mounted on non-conductive headform.	No dripping	Ignition, melting, and separation are permitted.

[1] Specific conditioning procedures are required for some items; garment materials and gloves are tested before and after 10 cycles of laundering.

[2] Tabulated information is abstracted from NFPA 1951. This standard should be consulted for detailed specification of test methods, performance requirements, and preconditioning protocols.

Table A11. NFPA 1951 Test Methods and Requirements for Measuring Conductive Heat Resistance. [1, 2]

Ensemble Component Tested	Test Method or Procedure	Performance Criteria	Comments
Gloves (composite) **Footwear (upper)**	ASTM F1060: Specimens of glove body placed on a hot plate set at 280°C (536°F). Stoll criteria is used to predict time to pain and to 2nd degree burn.	Predicted time to 2nd degree burn < 7 seconds; Predicted time to pain < 4 seconds.	Sample compressed at 0.5 psi. Wet and dry samples of gloves are tested.
Thread (garments)	FMS 191A,1534: Small piece of thread is subjected to Soxhlet extraction and then placed on heated microstage with observation of condition.	Melting temperature $\leq 260^{o}$C (500^{o}F)	Method is intended to determine thermal stability of thread under high heat conditions; may not relate to actual performance of seam.

[1] Specific conditioning procedures are required for some components; gloves are tested before and after 10 cycles of laundering and following wet preconditioning.

[2] Tabulated information is abstracted from NFPA 1951. This standard should be consulted for detailed specification of test methods, performance requirements, and preconditioning protocols.

Table A12. NFPA 1951 Test Methods and Requirements for Measuring Radiant Heat Resistance. [1, 2]

Ensemble Component Tested	Test Method or Procedure	Performance Criteria	Comments
Garment composite	ASTM F1939: RPP tester used to expose samples to radiant heat at 0.5 cal/cm^{2}sec. Stoll criteria used to predict time to 2nd degree burn injury.	RPP rating ≥ 8.0	Predicts radiant protective performance in high radiant heat. Static test; does not measure flammability or effects of thermal degradation.
Gloves (composite)	Same as garment composite.	RPP rating ≥ 7.0	Provides limited simulation of radiant heat exposures for gloves.
Footwear (upper)	Same as garment composite.	RPP rating ≥ 8.0	Provides limited simulation of radiant heat exposures for footwear.
Helmet	Top of helmet is sequentially exposed to combination of heat from radiant panel (1.0 w/m^2) and 1000 btu/ft^2 methane gas Bunsen burner flame.	Afterflame time < 5.0 seconds.	Specimen configuration is an issue. Provides indirect measure of thermal protective insulation.

[1] Specific conditioning procedures are required for some components; garment composite and glove composites are tested before and after 10 cycles of laundering.

[2] Tabulated information is abstracted from NFPA 1951. This standard should be consulted for detailed specification of test methods, performance requirements, and preconditioning protocols.

Table A13. NFPA 1951 Test Methods and Requirements for Measuring Water Absorption, Water Penetration, Liquid Penetration, and Viral Resistance. [1, 2]

Ensemble Component Tested	Test Method or Procedure	Performance Criteria	Comments
Garment	ASTM F1359: garment is placed on manikin over liquid absorptive garment and exposed surfactant treated water spray (32 dynes/cm) of 20 minutes in 4 different orientations.	No evidence of liquid or liquid absorption; the garment and the interior of the manikin.	Only whole garment test in NFPA 1951 Standard. Report interpretation based on subjective criteria.
Garment (composite)	AATCC 22: Repellency measured by rating fabric appearance after exposure to 500 mL of water through specified nozzle onto specimen at incline.	Repellency rating ≥80	Test based on subjective criteria.
Barrier layer and seams for garment, gloves, and footwear	ASTM F903, Procedure C: Samples exposed to fireground chemicals after conditioning for 1 hour, with one minute at 13.8 kPa (2 psi); penetration visually observed	Evidence of liquid in one hour, constitutes failure in test.	Test liquids are AFFF, battery acid, hydraulic fluid, surrogate gasoline fuel C, and swimming pool chlorinated chemical.
Barrier layer and seams for garment, gloves, and footwear	ASTM F1671: Samples exposed to biochallenge solution after conditioning for 1 hour, with one minute at 13.8 kPa (2 psi); penetration based on bioassay method involving rinse of sample interior surface following exposures.	Evidence of viral penetration, in one hour, constitutes failure in test.	Phi-X-174 Bacteriophage is used as surrogate for blood borne pathogen.

[1] Specific conditioning procedures are required; overall garments, garment composite, garment barrier layer and seams, and glove barrier layer and seam are tested after 10 cycles of laundering.

[2] Tabulated information is abstracted from NFPA 1951. This standard should be consulted for detailed specification of test methods, performance requirements, and preconditioning protocols.

Table A14. NFPA 1951 Test Methods and Requirements for Measuring Total Heat Loss and Element Function. [1, 2]

Ensemble Component Tested	Test Method or Procedure	Performance Criteria	Comments
Garment Composite	ASTM F1868, Procedure C: Composite materials are laid flat on sweating hot plate with measurement of thermal and evaporative resistances.	THL $\geq$ 450 w/m^2.	Measures breathability of flat garment composite samples.
Gloves	Liner Retention Test: Assesses liner retention after multiple launderings of whole gloves.	Glove donning time $\leq$ baseline time plus 20 seconds.	Evaluates effect of gloves on hand functions - donning, dexterity, and grip.
	Dexterity Test: Time for test subjects to place pegs in pegboard is measured with and without gloves.	Dexterity time with gloves $\leq$ 200 percent greater than barehanded value.	
	Grip Test: Weight that can be lifted by test subjected using halyard and pulley Is measured with and without gloves.	Weight pulling capacity with gloves $\leq$ 80 percent bare handed value.	
Footwear	Ladder shank bend test: deflection of ladder shank is measured under 182 kg (400 lb) force.	Deflection $\leq$ 6 mm (0.25 in.).	Intended to keep footwear sole stiff when climbing ladders or walking on uneven surfaces.

[1] Specific conditioning procedures are required for some components; in dexterity test, gloves are evaluated after 10 cycles of laundering; in grip test, gloves are evaluated before and after 10 cycles of laundering, in both dry and wet conditions.

[2] Tabulated information is abstracted from NFPA 1951. This standard should be consulted for detailed specification of test methods, performance requirements, and preconditioning protocols.

Table A15. NFPA 1951 Test Methods and Requirements for Measuring Physical Properties.[1, 2]

Ensemble Component Tested	Test Method or Procedure	Performance Criteria	Comments
Garment materials (textile fabrics and linings)	ASTM D1424: Tear strength (Elmendorf tear method)	Tear strength ≥23 N (5 lb_f).	Tear strength of fabric materials is determined by fiber type, yarn, fabric weight.
Garment material (outer shell)	ASTM D5034: Breaking strength	Breaking strength ≥320 N (70 lb_f)	Grab strength type method is used.
	ASTM D3885:Stoll flex/abrasion method; ASTM D5035: Breaking strength	Breaking strength ≥230 N (50 lb_f)	Strip breaking strength evaluated after 500 cycles of abrasion.
Garment material seams (major A, major B)	ASTM D1683: Seam strength (for woven fabrics)	Seam strength ≥315 N (70 lb_f) (Major A seams); ≥180 N (40 lb_f) (Major B seams).	Seam requirements are based on their location in the garment, their function, and the type of materials used.
Gloves (composite) **Footwear (upper)**	ASTM F1790: Cut resistance	Cut distance >25mm (1 in.) at 200 g load (gloves); Cut distance >25mm (1 in.) at 800 g load (boots)	Measures distance of blade travel over material before cut through.
	ASTM F1342: Puncture Resistance	Puncture force >45N (10 lb_f).	Measures force of nail like probe to puncture composite.
	ASTM D3884: Abrasion resistance (Taber method)	No wear through outermost separable layer after 2500 cycles	Uses H-18 while to simulate hard grit surface
Footwear (sole and heel)	ANSI Z41: Puncture resistance:	Puncture force ≥1210 N (272 lb_f).	Same requirement as industrial footwear.
	ASTM F489: Static coefficient of fiction by James Machine	Slip resistance (static coefficient) ≥0.75 (dry).	Applied to both sole and heel materials (not sole samples).
	ASTM D1630: Footwear abrasion	Abrasion Index >65.	Compares mass removed versus pristine sample.

[1] Specific conditioning procedures are required for some components; garment breaking strength measured after 10 laundering cycles; garment seam strength and glove puncture resistance is tested after 5 cycles of laundering.

[2] Tabulated information is abstracted from NFPA 1971. This standard should be consulted for detailed specification of test methods, performance requirements, and preconditioning protocols.

Table A15. NFPA 1951 Test Methods and Requirements for Measuring Physical Properties. [1, 2] (continued)

Ensemble Component Tested	Test Method or Procedure	Performance Criteria	Comments
Footwear (sole)	Flex fatigue test: Observation of sole after 100,000 flexes	Cut growth ≤350%	Test simulates wear damage to sole.
Footwear (toe)	ANSI Z41: Impact/compression resistance	Impact resistance ≥ 101.7 J (75 ft-lb); compression resistance ≥13 mm at 11,121 N (2500 lb_f)	Same requirement as industrial footwear.
Helmets	Impact resistance test (force)	Transmission of force ≤3783 N (850 lb_f); No individual specimen transmits force greater than 4450 N (1000 lb_f)	Measures force transmission through helmet when struck by anvil
	Physical penetration test	No electrical contact	Specific weighted, blunt anvil dropped on helmet
	Retention system test	No failure	Force used to pull the retention system away from helmet
Helmet suspension systems	Suspension system retention test	Force required to separate suspension from helmet ≥ 2.3 kg (5 lb)	Force applied in pulling suspension system from helmet

[1] Specific conditioning procedures are required for some components; helmets/faceshield preconditions include low temperature, radiant heat, and wet conditioning.

[2] Tabulated information is abstracted from NFPA 1951. This standard should be consulted for detailed specification of test methods, performance requirements, and preconditioning protocols.

Table A16. NFPA 1951 Test Methods and Requirements for Measuring Miscellaneous Properties.[1]

Ensemble Component Tested	**Test Method or Procedure**	**Performance Criteria**	Comments
Garment materials (outer shell, liquid barrier, and liners)	AATCC 135: Cleaning shrinkage; measured after 10 cycles of laundering.	Shrinkage ≤5%.	Set acceptable shrinkage as 1 size difference.
Garment trim **Helmet trim**	Retroreflectivity and fluorescence test: Special device is used to measure nighttime brightness of trim new, following laundering and heat exposure, and during rainfall; assessment of fluorescence based on observation	Coefficient of retroreflectivity ≥ 100 cd/lux/m^2 (cd/fc/ft^2); trim designated as fluorescent..	Fluorescence is not measured, only observed
Product labels (garments)	Label legibility test: Label examined for legibility following washing, heat exposure, and light abrasion	Labels remain legible.	Interpretation of pass/fail is subjective
Helmets	Electrical insulation test (helmets): evaluates helmets against 50-Hz AC.	Current leakage ≤ 3 mA.	Current flow through helmet in two procedures
Footwear	ASTM F1116: 14,000 V exposure with conductive metal shot inside boots	Current leakage ≤ 5 mA.	Different requirement applied to footwear as compared to helmets
Hardware (garments, gloves, footwear, helmets)	ASTM B117: corrosion resistance measured with 5% salt spray for 20 hours	Inherently resistant metals must show no more than surface-type corrosion or oxidation; ferrous must show no corrosion of base metal; hardware must remain functional.	Interpretation of pass/fail is subjective

[1] Tabulated information is abstracted from NFPA 1951. This standard should be consulted for detailed specification of test methods, performance requirements, and preconditioning protocols.

Table A17. NFPA 1994 Test Methods and Requirements for Measuring Ensemble/Component Integrity. [1,2]

Ensemble Component Tested	Test Method or Procedure	Performance Criteria			Comments
		Class 1	Class 2	Class 3	
Ensemble of garment, gloves, and footwear	Inward leakage test: test subject wears ensemble inside chamber with 1000 ppm SF_6 and performs exercises. Suit interior sampled and tested for levels of SF_6.	Inward leakage ≤0.02%.	Inward leakage ≤2.0%.		Test relies on sampling inside suit during exercises by test subject; sample acquisition may artificially affect ensemble performance.
	ASTM F1052: Ensemble inflated to pressure of 100 mm (4-in.) water gauge with monitoring of pressure at 4 minutes.	Ending pressure ≥80 mm (3.2-in.) for ensembles with and without external fittings.			Only applied to Class 1 ensembles; forces total encapsulation of wearer and respirator.
	ASTM F1359: garment is placed on manikin over liquid absorptive garment and exposed surfactant treated water spray (32 dynes/cm) in 4 different orientations.		No evidence of liquid or liquid absorption after 20 minutes. No collection of liquid inside gloves or footwear.	No evidence of liquid or liquid absorption after 4 minutes. No collection of liquid inside gloves or footwear.	Report interpretation based on subjective criteria.
Gloves, footwear	ASTM D5151 (modified): Gloves or footwear filled with 32 dynes/cm water and observed for 1 hour.		No evidence of leakage.	No evidence of leakage.	Separate subject test applied to gloves and footwear.
Ensemble exhaust valves	Suction of -25 mm water column pressure applied with measurement of leakage.	Exhaust valve flow rate ≤30 ml/min.			Permits separate evaluation of exhaust valve one-way performance.

[1] Specific conditioning procedures are required for some components; ASTM F1052 testing of Class 1 ensembles and ASTM F1359 testing of Class 2/3 ensembles is performed after ensembles are subjected to simulated use per ASTM F1154.

[2] Tabulated information is abstracted from NFPA 1994. This standard should be consulted for detailed specification of test methods, performance requirements, and preconditioning protocols.

Table A18. NFPA 1994 Test Methods and Requirements for Measuring Material Barrier Performance. [1,2]

Ensemble Component Tested	Test Method or Procedure	Performance Criteria			Comments
		Class 1	Class 2	Class 3	
Garment, visor, and glove material and seams; footwear upper	ASTM F739 (modified): Permeation resistance against chemical warfare agents; permeation measured using test cell where specimen divides cell into 2 hemispheres; challenge on exterior side of specimen; other side analyzed for permeant.	Cumulative permeation ≤ 1.25 $\mu g/cm^2$ (GB, VX); permeation ≤ 4.0 $\mu g/cm^2$ (HD, L); Challenge concentrations at 100 g/m^2 (1-hour)	Cumulative permeation ≤ 1.25 $\mu g/cm^2$ (GB, VX); permeation ≤ 4.0 $\mu g/cm^2$ (HD, L); Challenge concentrations at 10 g/m^2 with closed top configuration of test cell (1-hour)	Cumulative permeation ≤ 1.25 $\mu g/cm^2$ (GB, VX); permeation ≤ 4.0 $\mu g/cm^2$ (HD, L); Challenge concentrations at 10 g/m^2 with open top configuration of test cell (1-hour)	Differences in permeation challenge account of surface concentration of agent and configuration of cell to provide hierarchy of exposure among ensemble classes. Agent test end points based on cumulative permeation amounts.
	ASTM F739 (modified): Permeation resistance against toxic industrial chemicals (gases)	Breakthrough time ≥60 minutes; gas concentrations at 100% (NH_3, Cl_2, AC, CG, CK).	Breakthrough time ≥60 minutes; gas concentrations at 1000 ppm (NH_3, Cl_2, AC, CG, CK).		Class 1 and 2 ensembles are only tested for gases, with lower concentration for Class 2 materials and seams.
	ASTM F739 (modified): Permeation resistance against toxic industrial chemicals (liquid)	Breakthrough time ≥60 minutes (DMA); same conditions as agents	Breakthrough time ≥60 minutes (DMA); same conditions as agents	Breakthrough time ≥60 minutes (DMA); same conditions as agents	Same approach is used as for chemical agents, except breakthrough time is measured.
	ASTM F1671: ASTM F1671: Samples exposed to biochallenge solution for 1 hour, with 1-min at 13.8 kPa (2 psi); bioassay procedure used to determine penetration of microorganisms.		No penetration after 1-hour.	No penetration after 1-hour.	Viral penetration test is not applied to Class 1 tests because of rigorous permeation resistance criteria already applied to ensemble materials and seams.

[1] Specific conditioning procedures are required for some components; Garment materials are subjected to 45 cycles of flexing (ASTM F392) and 100 cycles of abrasion (ASTM D4157); gloves are subject to full cycle of dexterity testing; footwear is subject to 10,000 flexes (FIA 1309).

[2] Tabulated information is abstracted from NFPA 1994. This standard should be consulted for detailed specification of test methods, performance requirements, and preconditioning protocols.

Table A19. NFPA 1994 Test Methods and Requirements for Measuring Functional Performance. [1,2]

Ensemble Component Tested	Test Method or Procedure	Performance Criteria			Comments
		Class 1	Class 2	Class 3	
Ensemble of garment, gloves, and footwear	ASTM F1154: Assessment of function; stationary exercise and simulated response tasks performed by test subject.	Wearer able to complete all tasks, see through visor with visual acuity of 20/35 or better; ensemble accommodated hardhat.	Wearer able to complete all tasks, see through visor with visual acuity of 20/35 or better; ensemble accommodated hardhat.	Wearer able to complete all tasks, see through visor with visual acuity of 20/35 or better; ensemble accommodated hardhat.	Test addresses impact of wearing ensemble on wearer function.
	Maximum ventilation rate test: determined by flowing air into ensemble through pass-through at rate of 500 L/min; pressure monitored during airflow; gas-tight integrity measured per ASTM F1052 following airflow.	Internal pressure does not exceed 100 mm (4-in.) water guage during test; ending suit pressure for inflation test ≥80 mm (3.2-in.)			Test intended to prevent over-inflation of ensemble without damage to ensemble integrity; applied only to Class 1 ensembles.
Gloves	Dexterity Test: Time for test subjects to place pegs in pegboard is measured with and without gloves.	Dexterity time with gloves ≤ 600 percent greater than barehanded value.	Dexterity time with gloves ≤ 450 percent greater than barehanded value.	Dexterity time with gloves ≤ 300 percent greater than barehanded value.	Hierarchy of performance by ensemble class based on the assumptions that less barrier protection permits better hand function.

[1] Tabulated information is abstracted from NFPA 1994. This standard should be consulted for detailed specification of test methods, performance requirements, and preconditioning protocols.

Table A20. NFPA 1994 Test Methods and Requirements for Measuring Component and Material Physical Properties. [1]

Ensemble Component Tested	Test Method or Procedure	Performance Criteria			Comments
		Class 1	Class 2	Class 3	
Exhaust valves	Exhaust valve pull out strength test: force applied in pulling out valve from garment	Failure ≥ 135 N (30 lb_f)			Only applied to encapsulating suits (Class 1 ensembles); higher force applied to external fittings because these fittings are used for umbilical and cooling air.
External fittings	Fitting pull out strength test: force applied in pulling out valve from garment	Failure ≥ 1000 N (225 lb_f)			
Garment material **Visor material**	ASTM D751 (ball burst)	Burst force ≥ 200 N (45 lb_f).	Burst force ≥ 156 N (35 lb_f).	Burst force ≥ 134 N (30 lb_f).	Hierarchy of performance by ensemble class.
	ASTM D2582: Puncture propagation tear resistance	Tear resistance ≥49 N (11 lb_f).	Tear resistance ≥31 N (7 lb_f).	Tear resistance ≥25 N (5.6 lb_f).	Measures resistance of material to snagging.
	ASTM D747 (modified): Bending moment (for garment materials); ASTM D2136 (for visors)	Bending moment ≤0.057 Nm at -25^{o}C No fracture damage for visors.	Bending moment ≤0.057 Nm at -25^{o}C No fracture damage for visors.	Bending moment ≤0.057 Nm at -25^{o}C No fracture damage for visors.	Intended to measure cold temperature performance; visors tested with different method.
Garment visor material seams; Garment closure	ASTM D751 (seam strength)	Seam strength ≥2.63 kN/m (30 lb_f/2-in.).	Seam strength ≥1.31 kN/m (15 lb_f/2-in.).	Seam strength ≥1.31 kN/m (15 lb_f/2-in.).	Hierarchy of performance by ensemble class.
Glove material **Footwear (upper)**	ASTM F1790: Cut resistance	Blade travel ≥ 25 mm (1-in.) at 90 g (gloves) and 800 g (footwear).	Blade travel ≥ 25 mm (1-in.) at 75 g (gloves) and 600 g (footwear).	Blade travel ≥ 25 mm (1-in.) at 60 g (gloves) and 400 g (footwear).	
	ASTM F1342: Puncture resistance	Puncture force ≥22 N (5 lb_f) (gloves) ≥36 N (8 lb_f) (footwear)	Puncture force ≥26.5 N (3.7 lb_f) (gloves) ≥27 N (6 lb_f) (footwear)	Puncture force ≥11 N (2.5 lb_f) (gloves) ≥18 N (4 lb_f) (footwear)	

[1] Tabulated information is abstracted from NFPA 1994. This standard should be consulted for detailed specification of test methods, performance requirements, and preconditioning protocols.

Table A20. NFPA 1994 Test Methods and Requirements for Measuring Component and Material Physical Properties.[1] (continued)

Ensemble Component Tested	Test Method or Procedure	Performance Criteria			Comments
		Class 1	Class 2	Class 3	
Glove material **Footwear (upper)**	ASTM D747 (modified): Bending moment	Bending moment ≤0.057 Nm at -25^{o}C	Bending moment ≤0.057 Nm at -25^{o}C	Bending moment ≤0.057 Nm at -25^{o}C	Same as garment and visor materials.
Footwear (sole)	ANSI Z41: Puncture resistance:	Puncture force ≥1.21 kN (272 lb_f).	Puncture force ≥1.21 kN (272 lb_f).	Puncture force ≥1.21 kN (272 lb_f).	Same requirement applied to each ensemble class.
	ASTM D1630: Footwear abrasion	Abrasion Index >65.	Abrasion Index >65.	Abrasion Index >65.	
	ASTM F489: Static friction coefficient	Friction coefficient ≥0.75 (dry).	Friction coefficient ≥0.75 (dry).	Friction coefficient ≥0.75 (dry).	
Footwear (toe)	ANSI Z41: Impact/compression resistance	Impact resistance ≥ 101.7 J (75 ft-lb); compression resistance ≥13 mm at 11,121 N (2500 lb_f).	Impact resistance ≥ 101.7 J (75 ft-lb); compression resistance ≥13 mm at 11,121 N (2500 lb_f)..	Impact resistance ≥ 101.7 J (75 ft-lb); compression resistance ≥13 mm at 11,121 N (2500 lb_f).	

[1] Tabulated information is abstracted from NFPA 1994. This standard should be consulted for detailed specification of test methods, performance requirements, and preconditioning protocols.

APPENDIX B

REFERENCES

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