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The Evolution of Protective Equipment for Disaster Response

Christina Baxter, Emergency Response TIPS, LLC
Jeff Stull, International Personnel Protection, Inc.

Introduction

This chapter focuses on the evolution of protective clothing for firefighting, special operations, and hazardous materials/CBRN threats. In addition, it covers heat stress management and respiratory protection.

Throughout this chapter there are references made to applicable voluntary consensus standards. Beginning in 1995, there was a push by the federal government to avoid duplication of efforts in standards development; allow the national economy to operate in a more unified fashion; and to enhance quality and safety by allowing Government personnel to use products and components designed for the commercial marketplace. The following documents support the use of voluntary consensus standards in the DoD operating environment:

- Public Law 104-113, the National Technology Transfer and Advancement Act of 1995 [1];
- Public Law 108-237, Standards Development Organization Advancement Act of 2004 [2];
- Office of Management and Budget's Circular Number A-119, Federal Participation in the Development and Use of Voluntary Consensus Standards and in Conformity Assessment Activities [3];
- DoDM 4120.24, Department of Defense Instruction: Defense Standardization Program [4]; and,
- SD-9, DoD Guidance on Participating in the Development and Use of Non-Government Standards [5].

During his tenure as the Assistant to the Secretary of Defense (Nuclear, Chemical, and Biological Defense Programs) from 2001 through 2006, Dale Klein released several guidance memos to the defense CBRN community regarding the implementation of national consensus-based standards, specifically those from the National Fire Protection Association (NFPA) and the National Institute for Occupational Safety and Health (NIOSH) [6, 7].

Fire-Fighting Protective Clothing

With the rise of new material and product requirements, gloves have been developed from ordinary insulated leather work gloves to multi-layered glove products that mimic some of the characteristics of garments, but with design intended for achieving balance between thermal protection, moisture protection, and hand function. While earlier firefighter footwear used high-temperature rubber coated boots, the latest trend has been toward lighter-weight, breathable, and more form-fitting leather footwear that uses similarly breathable moisture barrier layers coupled with internal thermal linings.

Firefighter helmets have probably shown somewhat less progression because the leather helmet design has become relatively iconic within the fire service. While new high-temperature-resistant thermoplastic materials are used in the majority of firefighter helmets, many helmet designs retain the same rib-based construction that was fundamental to the design of leather helmets. Nevertheless, the promotion of lighter-weight materials coupled with features such as ear covers and face/eye protection, has elevated levels of head and neck protection. Helmets are now supplemented with protective hoods, which are a relatively new addition to the overall protective ensemble.

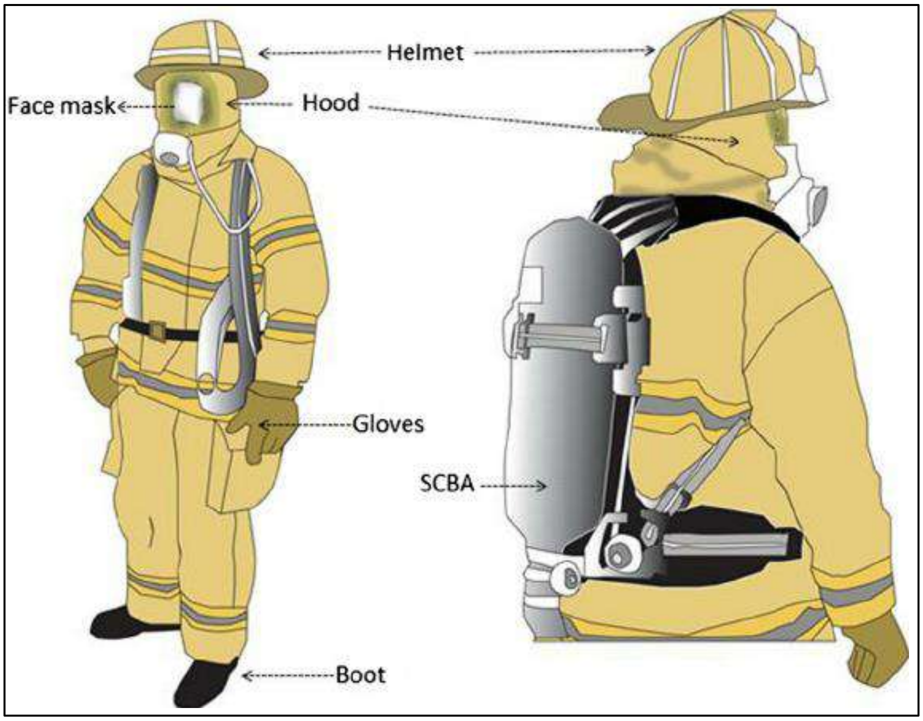

Figure 1. Configuration of modern turnout gear for firefighters (Courtesy Cornell University, Fiber Science and Apparel Design Department, College of Human Ecology)

Current Products

Modern turnout gear (see Figure 1) is designed using three protective layers: a thermal barrier; a moisture barrier; and an outer shell. The thermal barrier is generally made of aramid-based non-woven or batting materials that are then quilted to a flame-resistant facecloth for support. The quilted design creates more dead air space without adding weight. The makeup of the thermal liner is critical to the comfort and safety of firefighters, as it has the greatest impact on thermal protection and a significant role in affecting heat stress. The moisture barrier, often constructed from bicomponent polytetrafluorethylene and polyurethane film laminated to an aramid fabric, provides resistance from water, chemicals, and viral agents. While this layer of the clothing composite primarily functions as a barrier, it substantially affects the ability of clothing to release both evaporative and conductive heat, as well as contributing to the overall clothing system installation. The outer shell, generally made from an aramid and polybenzimidazole blend, provides primary physical protection for the individual wearer and for the underlying layers. All clothing layers are required to be flame and heat-resistant. Therefore, the specific layers and components used in current products are those that meet the respective performance characteristics. In addition, turnout clothing utilizes multiple features, such as high visibility trim, reinforcement layers for physical protection, and supplemental layers for additional insulation at critical areas such as the shoulders, where compression is likely to take place.

The turnout clothing industry includes a large number of manufacturers which use many of the same outer shell, moisture barrier, and thermal barrier layers, as well as supplemental materials and hardware in the construction of their clothing. The majority of clothing is manufactured as coats and pants designed to be worn as a set, with appropriate areas of overlap and interface with other ensemble elements. Manufacturers distinguish their products by the implementation of different design features that affect fit and function, though most of these designs share common attributes particularly as it relates to closures, reinforcement areas, and placement of high-visibility trim as dictated by the NFPA 1971 standard.

The NFPA 1971 standard has also affected the evolution of available products for the remainder of the protective ensemble. Helmets are classified as either having a traditional (leather-like) or modern design, where the latter uses a more efficient smooth helmet shell. All helmets include a suspension system that allows for positioning and adjustment of the helmet on the firefighter's head. Helmets must be provided with either a set of flame-resistant goggles or a face shield for eye protection in the event that the firefighter is not wearing their self-contained breathing apparatus (SCBA) facepiece. Some newer helmet designs incorporate retractable face shields.

Multiple types of gloves are used in structural firefighting from a range of different manufacturers. The large majority of these gloves use an outer shell of a durable, heat-resistant leather combined with either one or two underlying layers for moisture and thermal protection. Some glove products have transitioned to outer fabric layers (particularly on the back of the glove) that must be supplemented with an additional insulation material. Depending on the glove material littering and design, ensuing gloves have varying impact on firefighter hand function.

Firefighter footwear includes both rubber and leather styles. The latest trend in footwear products is toward lighter weight, increased flexibility, better ankle support, and improved slip resistance (or traction). All footwear must be at least 12 inches in height as measured from the footwear interior. A variety of manufacturer designs also have introduced fabrics into a portion of the footwear exterior. Most footwear styles are of a slip-on design but others use gussets and other waterproof closure systems.

Whereas firefighter protective hoods have generally been two-layer flame resistant knit, sock-like products with a hood opening to accommodate the SCBA facepiece visor, a new generation of hoods has been recently introduced into the marketplace. These new hoods incorporate a particulate-blocking layer that is intended to limit the amount of soot particulates reaching the firefighter's face. The advent of these new hoods has been in recognition of specific concerns firefighters now face with continuing exposure to fireground contaminants [8, 9].

Challenges with Current Products

Balancing Thermal Protection and Heat Stress

Over the past decade, firefighter turnout gear has seen a great increase in its thermal protection capabilities (by increasing insulation) and in the reduction of many steam burns (through the inclusion of moisture barriers). Unfortunately, the increase in thermal protection comes with an increase in the thermal burden to the wearer that can create physiological stress and limit firefighter time on scene. McQuerry et al. studied the component layers of turnout gear individually and in combination, and demonstrated that the inclusion of the moisture barrier provided the most resistance to heat loss and, therefore, played a large role in overall thermal burden [10]. For this reason, thermal protection is balanced with total heat loss. However, new information is emerging that the measurement of total heat loss may not provide a complete picture for predicting the impact of clothing on the wearer under different environmental conditions. The fire service industry is now studying evaporative resistance as either a replacement or as a supplemental measurement for understanding the physiological impact of material choices on firefighter heat stress [11]. In addition, the use of multiple reinforcements as well as pockets, and other supplemental layers warrants further study for efficiently designing turnout clothing to lessen stress on the firefighter.

Minimizing Firefighter Exposure to Products of Combustion

There are many combustion byproducts observed in structure fires, but the major ones include:

- Carbon monoxide [12–16]
- Nitrogen dioxide [12–14, 16–18]
- Sulfur dioxide [14, 18–23]
- Hydrogen cyanide [12–15, 18, 24–30]
- Hydrogen chloride [12, 15, 19, 31, 32]
- Hydrogen fluoride [15, 21, 33]
- Hydrogen bromide [19, 31, 32, 34–36]
- Phosphoric acid [21, 37–40]
- Nitric acid [15]
- Sulfuric acid [15, 18]
- Volatile organic compounds (VOCs) [13–15, 18, 41–44]
- Aldehydes [13–15, 18, 43]
- Polycyclic aromatic hydrocarbons (PAHs) [14, 15, 41, 42, 44–49]
- Phthalate diesters [48, 49]

According to the International Association of Firefighters (IAFF), 55 percent of line-of-duty firefighter deaths since 2002 were caused by occupational cancer [50]. Studies such as those described above have definitively shown the deposition of carcinogens onto firefighter gear and their skin, and the need for gross decontamination, showering, and laundering of gear. However, in a 2017 study, Harrison et al. surveyed 485 firefighters from four departments about their post-fire decontamination behaviors and found that while the firefighters had positive attitudes regarding post-fire decontamination, showering after a fire was the only decontamination process occurring regularly [51]. Cleansing wipe use, gear laundering, and other behaviors occurred less frequently mainly due to department resources (time and equipment) or wet gear concerns [51].

The routes of entry of airborne contaminants generated in a fire into the body include inhalation, ingestion, dermal, and injection. The most significant route of entry is through inhalation [52]. The contaminants (gases and particulates) can deposit or pass into the body through the lungs causing both acute and chronic adverse health effects. Despite the importance of this entry route, its significance within the firefighting environment should be considered in the context of firefighters' use of SCBA and their tactical methods.

Airborne contaminants (gases and particulates) generally will not be ingested because of good hygiene practices and the use of SCBA. However, the importance of the skin as an entry route is less certain. For example, it has been known for approximately 200 years that certain illnesses are likely associated with dermal absorption of occupational or environmental contaminants, but this association is not clear for all exposures. [53]. It is well established that polycyclic aromatic hydrocarbons, aromatic hydrocarbons, and acid gases will be absorbed directly from the vapor phase and penetrate the skin. The penetration rate is dependent on many factors and the dose is also affected by the body's ability to de-toxify and excrete the contaminant. There is increasing evidence reported highlighting the importance of the skin as an entry route in the context of firefighting [41, 47, 54, 55]. Given the extensive use of SCBA within the firefighting environment, the importance of the skin as an entry route has likely been underestimated.

Future Directions

New Materials to Increase Thermal Performance While Maintaining Breathability
There are several approaches being evaluated in this arena. One approach to increase thermal performance without reducing breathability is to maximize air insulation between layers. Another is to incorporate new, lighter materials which may provide a reduction in thermal liner thickness while maintaining similar thermal protective performance [56].

Ensemble Designs to Minimize Exposure to Products of Combustion
Manufacturers are designing the next generation of turnout gear with a specific goal to reduce the smoke and soot penetration through the ensemble interfaces. This approach to reducing the level of chronic exposures on the fireground could potentially result in a parallel reduction in cancer rates. Several approaches, including the use of smoke-impermeable fabrics at interface regions and inclusion of a removable bib onto the turnout gear pants are being considered [57].

Ensemble Cleaning
If frequent cleaning is to become the norm, then implications arise as to the impact on both the gear and the departments that choose to provide this level of cleaning. For years, many departments have struggled to outfit their members with two sets of gear. The push for two sets has been based on the argument that as one set becomes soiled or contaminated, an extra set is needed to prevent taking the unit out of service.

This two-set approach has been instrumental both in ramping up the ability to clean gear more frequently and in having cleaner gear available for fire department members.Yet, for some departments, a two-set approach may not be the solution or even possible within their available resources. This can occur because two sets are insufficient for a relatively busy station, or this simply creates a financial burden that a department cannot overcome.

In addition to the availability of clean gear, other questions have arisen regarding the ability to clean gear. Generally, the focus has been on garments, and to a lesser extent, more recently on hoods. This is because these items can be cared for much like regular apparel. Helmets, gloves, and footwear are generally more frequently ignored. Typically, these items cannot be machine-washed and sometimes are never cleaned after a fire incident. Yet, it is well recognized that these items become just as dirty, if not more so than the full garments. Thus, the ability to clean these items effectively remains a significant variable as the trend for frequent cleaning is increased.

Ensemble Durability for Increased Laundering

Even when it is possible to implement more frequent cleaning, there is still the issue of how cleaning can affect the long-term protective performance of the clothing and equipment. Regular cleaning can break down clothing over time. In the case of turnout clothing, only rudimentary controls are built into NFPA 1971 for making this assessment.

For most performance requirements within NFPA 1971 as a prelude to testing, only five cycles of laundering are applied for garments. For one property in particular—moisture barrier effectiveness—that number is increased to only 10 washing and drying cycles. Thus, if the expectation is that clothing is cleaned after every working fire, then some gear can be subjected to up to 25 cycles a year

Many manufacturers currently indicate that clothing generally has a service life, ranging from five to seven years for a moderately busy department. While it is recognized that many components are indeed quite rugged and durable, there remains some uncertainty as to whether frequent cleaning will cause some degradation of clothing and equipment performance. However, it is important to note that the flame resistance of the turnout gear is due to the base fibers used in the material, therefore, degradation in flame resistance is not expected.

Ensemble Issuance

The current system of PPE design, materials, cleaning, and decontamination may not be the best solution for managing firefighter exposure to contaminants. To address this problem more holistically, it may be necessary to think completely outside the box with respect to existing practices. Turnout clothing availability may be better served by clothing that is maintained by the department and issued as needed—meaning that gear is no longer specific to the individual, but to the organization. This approach creates significant problems such as ensuring appropriately sized ensemble elements for each firefighter, but it does provide a basis for ensuring that clean items are provided for each incident to the firefighter. Such practices are already being employed for protective hoods, a much simpler item of protective clothing.

What is clear from these issues is that conventional approaches probably will not provide long-term solutions and therefore other forms of technology, perhaps borrowed from other industries and adapted for the fire service, or altogether unique designs and techniques, should be considered to address the minimization of continued firefighter exposure to carcinogenic and other hazardous contaminants.

Special Operations Protective Clothing

Emergency responders in urban SAR (USAR) have to be prepared for potential exposure to a number of hazards (see Figure 2). Each response is different and the available protective clothing and equipment must provide adequate protection against each hazard. The unique nature and combination of these hazards warrant specialized clothing and equipment to protect emergency responders in the various missions they undertake. These requirements are generally different from those needed for related emergency response missions, such as structural firefighting, hazardous materials response, and emergency medical services.

Figure 2. This training exercise demonstrates the typical USAR protection worn during operations. (Photo courtesy of the authors)

Consequently, separate types of protective clothing and equipment have been established for special operations areas. While some elements of performance from each conventional response area are similar to those needed in USAR, USAR activities generally involve lower levels of the different hazards for longer potential exposure period and thus dictate specific requirements. Historically, practices for protecting emergency responders in special operations have varied dramatically throughout the country. In the past, depending on the type of mission, emergency responders from two different organizations would use completely different protective clothing in responding to similar incidents. Therefore, USAR protection strategies varied, as did the required missions to which rescuers respond. With little guidance previously being available, most emergency responder-based clothing and equipment purchases were based on experience but were unable to anticipate all possible situations or hazards.

Special operations evolved in the late 1980s when municipal and regional fire and police departments recognized special needs for more efficiently dealing with certain types of events. This recognition also took place at a national level through FEMA, which set up regional USAR teams. The specialized groups within the individual departments or regional teams created capabilities for addressing the following types of emergencies:

- Building/structural collapse
- Vehicle/person extraction
- Confined space entry
- Trench/cave-in rescue
- Search operations (air, water, terrestrial)
- High angle rescue
- Swift or still water rescue
- Contaminated water diving

The principal types of hazards associated with these events are generally physical in nature, but responders could also encounter flame and heat, such as incidental flash fire, exposure to chemicals and biological pathogens, and extremes of weather. The key separating elements for these types of missions as compared to more conventional emergency response were the longer length of mission time expected for the first responder were at lower protection levels.

Relative to the protection needs of their response, three different types of ensembles are categorized with the first area addressing extended physical protection needs and collectively referred to as technical rescue and separate areas for both swift/still/ice water rescue and contaminated water diving. For technical rescue, ensembles were defined as garments, helmets, gloves, and footwear for extended wearing operations. Potentially rugged physical environments demanded durable and physical hazard resistant clothing, which could be comfortably worn for long periods. For many of these operations, the potential also existed for exposure to incidental flame, or flash fire dictating the need for flame resistance, and in some cases included exposure to chemicals and blood-borne pathogens where a disaster scene may have caused the rupture and distribution of hazardous chemicals or during events where victims or bodies must be removed from the emergency scene. In many cases, emergency responders also need to be relatively visible to ensure their identification and prevent accidents at high-activity emergency sites. These clothing systems currently differ from turnout clothing by being substantially lighter and more functionally-oriented.

Swift water rescue and related emergency water operations defined a different type of ensemble that generally included garments that keep the wearer dry, warm, and protected against physical hazards such as debris and exposure hazards such as contaminated water. Ensemble elements such as helmets, gloves, and footwear all have to be devised for the difficult environment of rapidly moving water. Thus, helmets include perforations to prevent individuals being affected by current, special boots or fins are used to enable swimming or traversing uncertain bottom surfaces, and tethers are used for securing individuals. The ensembles are complemented with a personal flotation device, and other accessories to enable rescue activities.

Contaminated water diving, protective ensembles have similar features, but are designed for appropriate buoyancy and ensuring that individual responders are fully covered by their protective clothing and equipment to prevent any exposure to contaminated water. These systems must further integrate with self-contained underwater breathing apparatus (SCUBA). In some cases, ensembles have been developed to integrate with a surface supplied air system.

Current Products

Current products used in the technical rescue community are designed according to the following priorities: physical hazard protection from rough surfaces, jagged edges, pointed objects, and falling/flying debris; on-site visibility; clothing comfort, form, fit, and mobility; and, respiratory particulate protection. In addition, limited protection was necessary for: flame and heat; chemical flash-fire; and, electrical exposure. If chemical and biological detection is deemed necessary, products are cross-certified to the Hazmat/CBRN standards. In comparison to the turnout gear described previously, the special operations protective ensembles are meant to be lighter with less thermal insulation, more physically rugged, and intended for longer wearing times with a higher level of breathability. In addition, the current NFPA 1951 standard differentiates between utility technical rescue protective ensembles (exposure to physical and thermal hazards) and rescue and recovery protective ensembles (exposure to physical, thermal, liquid, and body fluid-borne pathogens).

Utility technical rescue garments tend to be rugged single-layer flame-resistant textile products using the form of coverall, many which are not certified to the NFPA 1951 standard. Some of these are similar to military battle dress uniforms. These products are supplemented by technical rescue helmets, gloves, and footwear. Several products are positioned against the NFPA 1951 standard for helmets and footwear; however, most special operations team personnel opt for heavy leather work gloves and wear examination gloves underneath their work gloves when liquid protection is needed. Extrication gloves that include a large number of reinforcements are also used by special operations teams for hand protection. Rescue and recovery garments comprise two basic design approaches: a single layer or two layers consisting of an outer shell and liquid barrier. Oftentimes, these are very similar to turnout gear but with limited thermal protection with the absence of the thermal barrier. These garments are combined with the same helmets, gloves, and footwear that are used for utility technical rescue operations.

Given their relative newness, there are no certified products to either the NFPA 1952 or 1953 standard on water rescue and contaminated water diving ensembles. Special operations teams requiring these capabilities use a combination of professional and sports equipment for these applications. For swift water rescue, conventional wet or dry suits are used with either kayak helmets or specialty professional products that have been represented for this application. Foot protection normally consists of neoprene water booties, sneakers, a nonslip boot, or swim fins. Dry suits are preferred where contamination may be suspected. Swim fins may greatly increase the speed of the rescuer in the water but their use takes training and frequent use to be an advantage. U.S. Coast Guard (USCG) Type III personal flotation devices (PFDs) are typically used; these PFDs have a sewn-in chest harness with a quick release buckle for the tether. Chest harnesses should have an attachment point on the back near the shoulder blades to tether a rescuer to rope as well as a one-hand release.

For contaminated water diving, a number of diving suit products have been positioned in the marketplace specific to contaminated water operations. These suits are fabricated from hybrid rugged rubber materials with demonstrated chemical resistance against a variety of products under use conditions and include high end closures and interface devices for attachment of diving gloves and booties with swimming fins. Most contaminated water diving suits share features with U.S. Navy products, which have gone through extensive validation testing. These suits are mated to a diving helmet and SCUBA system through a neck dam. However, many public safety diving systems use standard SCUBA worn over hoods and rely on the face-seal and hood mask seal for minimizing contaminated water contact with the wearer. These systems often require buoyancy controls and bail out systems.

Challenges with Current Products

Unfortunately, with some exceptions, there is a lack of selection for gear designed specifically for SAR missions, as there are currently no full ensembles certified to existing standards. For technical rescue operations, most products currently in use are adaptations from the products certified to NFPA 1971 or NFPA 2112, *Standard on Flame-Resistant Clothing for Protection of Industrial Personnel Against Short-Duration Thermal Exposures from Fire* [58], though there are several garment and footwear products that have been certified with other standards such as for emergency medical applications. Some of the problems with industry acceptance of the standards are that many requirements remain overly rigorous, particularly when associated with barrier testing of materials and products. Several current products that have been deemed acceptable either cannot be certified, or the costs for certification are prohibitive when weighed against the volume of products sold for this specialty area. Therefore, changes in the standards may induce more certified products, but the changes needed to be coupled with realistic expectations of performance.

Specific to the area of technical rescue, the fire service has wrestled with the concept of garment convertibility where structural garments can be reduced in a consistent way that does not compromise their use for high-end hazards but still allows the garment to be used for events such as vehicle extrication (see Figure 3), which require less thermal insulation. While this concept is not new, departments believe that since a large proportion of their responses are non-fire, there is utility in garment conversion or having their second garment be a technical rescue garment. The principal criticism of this approach is that technical rescue garment configurations will incorrectly be used in structural fire environments given their better mobility and greater comfort; however, these types of issues can be addressed through proper emergency scene management.

Future Directions

There are no radically new material and clothing design technologies on the horizon that would change the market or use of technical rescue protective clothing and equipment. It is likely that the use of technical rescue gear will remain limited to the true USAR missions for which it was originally intended. With shrinking budgets and the diminishment of federally-funded PPE, technical rescue gear will remain a specialized product instead of a lower tier of protection for the fire service. It is expected that innovative solutions will be sought for the ability to convert structural garments to technical rescue garments. Departments facing restricted budgets for PPE in increased focused on addressing hazards for contamination gear with products of combustion may undertake more creative solutions for the type of gear used in different missions to allow for better customization of the ensemble for the respective hazards.

Figure 3. Example of protection worn during extrication. (Photo courtesy of the authors)

Hazardous Materials/CBRN Protective Clothing

Current Products

Most chemical protective ensembles were designed for industrial applications and later adapted for emergency response use. It has only been the more recent ensembles designed to meet NFPA 1994 specifications that have been designed specifically for a disaster response scenario. Unfortunately, PPE is often purchased in small lots by a widely distributed network of independent procurement activities, especially in the U.S. This is due to the vast number of emergency response organizations, most of which are managed at the local level. The broad user profiles and the infrequent use of products leads to a slow research and development process by companies, as the procurement rate does not allow manufacturers to amortize the development costs in a timely manner. In addition, there are significant mission and cultural differences within the emergency response community, which has resulted in uneven adoption of existing standards and, in many cases, uneven adoption of the legal requirements set forth by OSHA.

Table 1 shows the products currently certified against the applicable chemical protective clothing standards. For NFPA 1992 and NFPA 1994, the 2012 and 2018 editions are both shown as the 2018 standard was recently released, therefore many products are in the process of gaining certification at the time the table was developed. At any point in time, a user is able to visit the websites of the Safety Equipment Institute and Underwriter's Laboratory to find lists of products certified against the NFPA standards by each of the certification programs. The products certified against NFPA 1991 and NFPA 1992 are very similar in design, while the ensembles certified against NFPA 1994 are predominantly more form-fitting and, in many cases, are not fully encapsulated.

<table>
<tr><th>Standard</th><th colspan="4">Certified Products</th></tr>
<tr><td>NFPA 1991 (2016 ed.)</td><td colspan="4">• Dupont RF600 (Reflector)
• Kappler Frontline 500
• Saint Gobain ONESUIT Flash 2
• Saint Gobain ONESUIT Pro 2
• Trellechem EVO
• Trellechem VPS Flash</td></tr>
<tr><td>NFPA 1992 (2018 ed.)</td><td colspan="4">• Blauer RC3
• Lion MT-94 Ruggedized
• Microchem by AlphaTec 68-4000</td></tr>
<tr><td>NFPA 1992 (2012 ed.)</td><td colspan="4">• Ansell 8017, 8057, 66-680, 66-683 (coats)
• Ansell 8018, 8058, 66-682 (overalls)
• Ansell 8016, 8056, 66-687 (coveralls)
• Dupont X3198T, C3199T, TP198T, TP199T
• Kappler ANC3E, Z3H426, Z3H427, Z3H428, Z3H432, Z3H437, Z3H576, Z3H577, Z3H579
• Saint Gobain ONESUIT Shield</td></tr>
<tr><td>NFPA 1994 (2012 ed.)</td><td>Class 1
Not Applicable</td><td>Class 2
• Blauer Multi-Threat
• Drager CPS 5900
• Kappler Zytron 500
• LION MT-94
• Saint Gobain ONESUIT Shield</td><td>Class 3
• Blauer XRT
• LION ERS</td><td>Class 4
• Blauer BRN-94</td></tr>
<tr><td rowspan="2">NFPA 1994 (2018 ed.)</td><td rowspan="2">Class 1</td><td>Class 2
• Trellechem ACT</td><td>Class 3
• No certifications awarded</td><td>Class 4
• No certifications awarded</td></tr>
<tr><td>Class 2R
• Lion MT-94 Ruggedized</td><td>Class 3R
• Blauer RC3</td><td>Class 4R
• No certifications awarded</td></tr>
</table>

Table 1. Products currently certified against the applicable chemical protective clothing standards (as of May 29, 2018).

Challenges with Current Products

Current Level A/NFPA 1991 Products are Design-limited

During a recent survey of the hazardous materials response community (398 respondents), the main concerns of the operators related to the Level A/NFPA 1991 ensembles were in priority order, physical hazard resistance, clarity of vision, fine hand function, field of vision, general mobility, liquid penetration, speaking communications, comfort, flame/heat resistance, and overall durability [59].

Limited Visibility

The greatest safety issue that remains today with all current Level A/NFPA 1991 ensembles is limited field and clarity of vision [59]. While several manufacturers have begun to address system "fogging" of the face piece, very few overarching design changes have been made to address the field of vision or the clarity.

Operational Utility of Gloves

Gloves have been designed to meet the level of protection necessary, but very little thought has gone into the design of gloves to meet the operational needs of the user. One issue frequently brought up by the operational community is the lack of comfort and fine hand function with the current gloves used in hazardous materials response [59].

Current Level A/NFPA 1991 Products are Over-Protective

In the responder survey mentioned above, the operational community perceived that the NFPA 1991 standard requirements were set at the correct levels of protection and felt that they should at a minimum have flame and heat resistance, and in many cases, flash fire protection. However, in the same survey, the responders stated that they very rarely or never came across small fires, flames, or chemical flash fires. In addition, the hazards that were most frequently seen included liquid exposures, gas/vapor exposures, liquefied gas leaks, and physical hazards. Unfortunately, in the desire to provide enhanced protection, manufacturers have had to forego design considerations that could greatly enhance comfort, mobility, and operational tactility.

Service Life Issues

The issue of longevity for chemical protective ensembles has been highly debated. Ensembles can be engineered using rugged materials to withstand repeated use and physical wear and tear so that acceptable levels of protection are provided. However, once an ensemble becomes contaminated, then the question arises whether the ensemble can be adequately decontaminated to permit further use. This topic has been the subject of extensive research that is captured in several sources [60-66].

While performance criteria have been factored into the NFPA standards to address ensemble and material ruggedness, the representation of the ensemble's service life has been left to the discretion of the manufacturer with the exception of NFPA 1994. NFPA 1994 specifically states within its scope that "the standard shall establish requirements for protective ensembles and ensemble elements for a single exposure at incidents involving CBRN terrorism agents." The committee developed this statement to require that CBRN protective ensembles be disposed of following any CBRN terrorism agent exposure; however, it recognized that ensembles could be repeatedly used if such exposure did not occur.

Storage Life Issues

Another related area of concern is the longevity of chemical protective suits when stored, but not used. All three standards require that the manufacturer report the "storage life" of their ensemble as part of the technical data package that is provided with the clothing. The committee set this requirement with the anticipation that some ensembles could be stored for an extensive period but could also deteriorate over time. Each NFPA standard establishes the following definition:

> Storage life—The life expectancy of the CBRN protective ensemble and ensemble elements from the date of manufacture when it is only stored and

inspected and has undergone proper care and maintenance in accordance with manufacturer's instructions, but not used, donned, doffed, or repaired [67].

The storage life is established by the manufacturer and must be reported in the user information provided in the ensemble. No specific criteria are provided for how the manufacturer establishes the storage life for its products.

Future Directions

Over the past ten years, great strides have been made in the chemical protective clothing marketplace. However, there are still many gaps to be filled.

Form-fitting Gloves
Most gloves currently in use in the CBRN environment are not breathable and have poor moisture management, resulting in significant discomfort for the wearer. In addition, the gloves are made with a thick butyl rubber with little focus on usability. AirBoss Defense, with funding from DoD, is developing a new glove providing greater tactility, durability, dexterity, breathability, and comfort when compared to the traditional gloves [68]. The glove has been designed to exceed the requirements set forth in NFPA 1994, Class 3.

Balancing Protection with Comfort
The most significant driver for current material technology is the various tests that are applied in qualifying product materials and components. Early philosophies towards the evaluation of protective clothing materials have involved relatively severe challenge conditions that minimize choices of products that can provide greater levels of comfort and function. The development of NFPA 1994 and its ensuing revisions has led to the classification of ensemble levels, unlike what had previously existed through the use of NFPA 1991/NFPA 1992 alone.

The recognition that many exposures will be incidental coupled with material technology that can achieve high levels of evaporative heat loss is leading to products that can be worn more comfortably and functionally under a range of conditions. Separating biological and radiological particle hazards from chemical hazards (as one part of the hazardous material PPE strategy) is another means for allowing first responders to have optimal levels of protection.

Non-Encapsulating Vapor-Protective Ensemble Designs
Over the past three decades, there has been considerable focus on the quality of totally encapsulating chemical protective suits representing Level A performance, which is further defined by compliance with NFPA 1991. Nevertheless, the use of Level A ensembles represents only a fraction of the overall use of PPE for hazardous materials response. Moreover, many of the exposure levels used in qualifying these ensembles is well in excess of the maximum exposure conditions responders face in actual incidents. Emergency responders increasingly desire more tactically-oriented ensembles for which encapsulating suits cannot deliver the requisite functional performance. To this end, there are different government-sponsored projects that are focused on providing new ensembles that use relatively high, but credible, levels of chemical resistance and overall integrity tests

for defining ensembles that can provide Level A performance. The acceptance of these products will likely change the spectrum of hazardous materials PPE.

Managing Heat Stress

Each of the types of protective clothing described previously in this chapter plays a role in the overall heat stress of the operator. The core temperature of the operator should be maintained at 37 degrees Celsius +/- 1 degree Celsius for continued normal body function [69]. The human body naturally maintains this equilibrium by balancing the rate of heat exchange between the body and the environment. Parameters affecting the total heat load on an individual are:

- Conduction, or the direct transfer of heat between and object and the operator;
- Convection, or the heat exchange between the operator's skin and the ambient air immediately surrounding the skin;
- Radiation, or the heat exchange between the operator's skin and the radiant temperature of the surroundings; and
- Evaporation, or the heat loss from the operator's body due to the evaporation of sweat from the skin surface.

When looking at the above parameters, it becomes obvious that the protective clothing will play a significant role in the amount of heat stress as it will affect all four parameters. Oftentimes, operators reach an uncompensable environment which could result in heat stress. The heat stress will manifest itself in progressively more serious ways, including heat rashes, heat syncope (fainting), heat cramps, heat exhaustion, and heat stroke.

The addition of protective clothing creates a microenvironment around the operator that becomes the driving force behind the heat stress. The operator can make educated decisions regarding selection of PPE with heat stress in mind, but choosing breathable materials where possible, reducing the total weight of the garment, and reducing the number of layers of material. In addition, engineering controls such as pre-cooling or operational/post-cooling can be implemented where feasible.

Current Products

Pre-Cooling

Products used for pre-cooling of operators prior to the donning of protective clothing include cooling vests, arm immersion, water-perfused suits, heliox, and ice slushy. In a study performed by Maley et al., it was determined that the ice slushy was the only method of pre-cooling that reduced the core temperature, while all others reduced the skin temperature [70]. For those reducing the skin temperature, the ice vest provided the most marked difference and demonstrated that time periods of pre-cooling greater than 20 minutes were not necessary.

Operational Cooling

Products used for operational cooling, or post-operational cooling, include ice phase change, non-ice phase change, liquid cooled, water immersion, evaporative, or hybrid systems. A recent market survey by Stewart et al. found 46 different products on the market for cooling from 15 different manufacturers with use cases in industry, sports, law enforcement, military, medical, hazardous materials, firefighting, and everyday use. The team has developed a database as a means of distributing technical and scientific data on system functionality [71].

Physiological Status Monitoring

Most commercially available physiological status monitors capture the operators' blood pressure, heart rate, respiratory rate, and skin temperature. The data is used for a variety of purposes including developing a baseline for the individual operator, monitoring status remotely, and in some cases, as indicators of overexertion. The most common physiological status monitors used in the emergency response community today are products from Hidalgo and Zephyr.

Challenges with Current Products

One of the most obvious problems with the current products on the market is that the technical data provided to the operational community is inconsistent. This is mainly due to the fact that no standards exist in the cooling field outside of test methods. In 2016, NIOSH released *Criteria for a Recommended Standard for Occupational Exposure to Heat and Hot Environments* [69].

Many of the cooling technologies that are available focus on cooling the skin which can be counterproductive for the operator. With the exception of those within the lower wrist, hands, and feet, blood vessels in other areas of the body will vasoconstrict with reduced temperatures. This narrowing of the blood vessels decreases blood flow to the skin's surface and minimizes the body's natural ability to cool itself using evaporative sweating. In addition, the extra weight of the cooling device can add physiological work to the operator, thereby increasing heart rate.

There are two different factors that are generally used as indicators of physiological stress in emergency operations—elevated core temperature and elevated heart rate. For operations involving chemical protective clothing, elevated core temperature is the first indication of heat stress due to the uncompensable environment created by impermeable materials including materials with multiple layers and air gaps. For operations involving significant weight of equipment, as often seen in bomb suits and firefighting, elevated heart rate may be the earliest indicator of physiological stress. The U.S. Army Research Institute of Environmental Medicine (USARIEM) ECTemp™ algorithm has shown promise in estimating core temperature from heart rate, especially for those cases where impermeable materials are not in use [72]. As estimations do vary +/- 0.3 degrees Celsius from real measures, it is highly recommended that baseline information on operators is maintained to ensure application and operational safety.

Future Directions

Significant strides have been made in the past five years on understanding and managing heat stress, but this field still has significant room for growth.

Product Standard Development

Using the materials set forth by NIOSH in 2016, a standard setting organization, such as NFPA might develop a product standard to set the minimum technical requirements for cooling products, especially when used in combination with other protective equipment. The work performed by Ian Stewarts's team at the

Queensland University of Technology, which resulted in the development of the Cooling Database website will provide a first step in categorizing equipment by capability [71].

Non-Invasive Measures of Core Temperature

The deep body, or core, temperature of an individual is the measurement that drives the deleterious effects of heat stress. Unfortunately, the gold standard methods for measuring core temperature are the rectal thermometer and the esophageal thermometer, both of which are not operationally relevant to the disaster response community. There also are ingestible core body temperature sensors that can wirelessly transmit data as it travels through the digestive tract, but these must be administered several hours prior to an event to ensure that they are in the proper position for measurements and tend to have error rates similar to those observed with the ECTemp™ algorithm. This is often not possible for disaster response operations. Therefore, for operations where the driving factor his work rate related, such as work in bomb suits, firefighting gear, as well as SAR, the ECTemp™ algorithm should be utilized. For operations where uncompensable environments are due to chemical protective clothing, a non-invasive measure of core temperature should be developed or further studies on the ECTemp™ applicability to this environment should be performed. The research team from USARIEM published a technical report in 2016 detailing the past accomplishments and future defense needs in the field of physiological status monitoring [73]. In parallel, Pacific Northwest National Laboratory published a report on the use of physiological status monitoring in the first responder community [74].

Effects of Chronic Heat Exposure

All of the studies on heat stress have been performed on short exposures, generally in the minutes to hours timeframe. Little is known about the long-term effects of repeated exposures to high heat environments such as those in firefighting and within the microclimates of chemical protective clothing.

Heat Stress and Toxicology

It is widely accepted that increases in sweat and skin blood flow increase the dermal absorption of some toxicants [75, 76]. This becomes increasingly important when dealing with the disaster response arena, especially firefighting, as it is known that many of the toxicants are dermal threats.

Hydration Status Monitoring

Many methods, each with their own drawbacks, have been used over the years for monitoring the hydration status of an individual. Unfortunately, the ability to measure hydration status in a complex fluid matrix with many interconnected fluid compartments, is unlikely to have high accuracy when using only one technique. In a laboratory, measurements of plasma osmolality (concentration) and total body weight (estimating volume) are excellent indicators of hydration status. In the operational environment, the volume and concentration of available fluids are constantly fluctuating, and the use of non-invasive techniques such as total body weight (estimating volume) and urine color (estimating concentration) are more relevant [77]. Work has also been done correlating salivary osmolality as an indicator of hydration status, but the measure was very dependent upon the individual and their baselines, therefore not as applicable broadly [77, 78]. In parallel, Eccrine Systems, Inc. is working on a non-invasive, electronic sweat sensor capable of transmitting real-time data on human sweat [79]. There remains a need for the development of real time, non-invasive measures of fluid volume and concentration.

Heat Stress Calculators and Estimating Work-Rest Cycles
There are a variety of heat stress calculator tools available today. An excellent tool for estimating heat potential for heat stress, not involving impermeable protective clothing, is available online from the Queensland Government. The Georgia Tech Research Institute, in partnership with Queensland University of Technology, North Carolina State University, and the Netherlands Organisation for Applied Scientific Research, developed a heat stress calculator specific to disaster response PPE using machine learning functions across data from multiple human trials in various chemical protective clothing, turnout gear, and bomb suits [80]. The calculator is available as a tool within the Emergency Response Decision Support System. More work needs to be done to develop capabilities that are specific to the PPE worn and the work performed. The calculators should be used for mission planning versus operational tools.

Physiological Monitoring and Work-Rest Cycles
Physiological monitoring devices have gained popularity over the past 10 years in emergency operations. Guidance documents need to be developed to ensure that the data is used properly to develop individualized work-rest cycles based upon the physiological status of the operator. Once sufficient data is available for operators in disaster response scenarios, guidance can be provided to minimize the number of heat casualties seen in emergency operations.

Respiratory Protection

Many of the applications for disaster response involve different types of respiratory hazards:

- Structural fires often result in high levels of smoke (particles) and toxic gases;
- Wildland, forest, and other outdoor fires also create smoke and gases, but exposure is usually at lower levels because fire responders often do not get as close to the source of the fire;
- Building collapses or other disasters release chemical vapors and large concentrations of suspended particles;
- Hazardous materials emergencies often involve the release of chemical gases and vapors;
- Rescue or emergency medical operations may result in exposure to tuberculosis and other airborne pathogenic diseases; and
- Terrorism incidents may result in exposure to chemical warfare agents, toxic industrial chemicals, and biological pathogens or toxins.

Respirators protect the wearer from inhalation of harmful dusts (particles), chemicals, and other respirable substances. Respirators provide protection to the wearer by:

- Removing contaminants from the air (air-purifying); or
- Supplying an independent source of respirable air (atmosphere-supplying).

The first type of respirators includes chemical or particulate air-purifying respirators (APR) and powered air-purifying respirators (PAPR). Examples of atmosphere-supplying respirators include supplied-air respirators and self-contained breathing apparatus (SCBA).

Current Products
Currently certified NFPA 1981 products are listed in Table 2.

Standard	Products
NPFA 1981 (2013 ed.)	• Avon Protection Systems Deltair (300027, 300028, 300029, and 300030) • Draeger Safety UK PSSS5000/PSS7000 Series and PSS7000H series • Honeywell Safety Products (Sperian Respiratory) Titan • Interspiro, Inc. Spiromatic S8 • MSA Safety FireHawk M7 XT Air Mask and G1 SCBA • Scott Health & Safety, Inc. Air Pak 2013 CBRN, Air Pak X3 CBRN, and NxG7 CBRN
NFPA 1986 (2017 ed.)	No certifications awarded as of 29 May 2018; therefore, responders continue to use NFPA 1981 certified products.

Table 2. Certified NFPA 1981 products (adapted from www.seinet.org). Products certified to the NIOSH standards can be found on the NIOSH Certified Equipment List.

Challenges with Current Products
SCBA development has traditionally focused on the delivery of air, versus operational performance. More recently, the trend has been to increase performance with technology enhancements such as communications clarity, integrated sensing systems, data collection and display, and others. In addition, SCBA systems have been hardened for use in specific environments, but little change has been made in the system profile.

Breathing Rates
It is important to note that the NIOSH CBRN filter certifications for air purifying respirator canisters are tested at a constant breathing rate of 85 liters per minute. For disaster response operations, this respiratory flow rate is very low when compared to the International Organization for Standardization (ISO) metabolic rates and respiratory flow rates referenced within ISO/TS 16976-1:2015 [81]. However, studies by Hofacre and Richardson, using cyclic breathing rates with peaks at approximately 400 L/min, demonstrated that the products currently certified to the NIOSH CBRN standards are protective, even at the higher, cyclic respiratory flow rates [82].

Mask Interoperability
Most current products use either a positive-pressure mask for SCBA operations or a negative-pressure mask for APR operations. Unfortunately, this requires many operators to have multiple masks to maintain and creates an additional burden for fit testing.

Fire-Hardened Designs
Currently certified SCBA products on the market are hardened for both CBRN environments and structural firefighting needs. The high temperature needs of the

firefighting community in addition to reserve air requirements and personal alert safety system devices drive up the cost and complexity of SCBA products. While these enhanced capabilities are necessary when using an SCBA in firefighting operations, they are not critical when responding to the other disaster response scenarios. This led to the development of the NFPA 1986 standard where the operational community on the technical committee included operators from defense, hazardous materials, law enforcement tactical teams, and bomb squads.

Future Directions

Combination Unit Respirators

A Combination Unit Respirator incorporates two or more types of respiratory detection devices within one unit, for example a combination APR/SCBA, and allows the user to switch between modes of operation without doffing the respirator. One of the driving forces behind the lag in product development in comparison to the user-identified need for combination unit systems is the lack of guidance on performance requirements, switching mechanism design, and risk compensation. For example, the guidance on when respiratory protection is required, and to what level the protection is necessary, are very straightforward in terms of APR versus PAPR versus SCBA, but the line becomes blurred when a combination unit is employed. Currently, the system is certified to its lowest level of protection offered.

Manual and Automated Switching Mechanisms

When a combination unit respirator is employed, the operator must know how to safely and effectively switch modes of operation. There are currently several manual switching mechanisms that includes a physical toggle switch, filter covers, and others. There are automated switching mechanisms under development that detect changes in inhalation profile and research is also being performed on switching mechanisms actuated by a chemical detector. As you can imagine, this is a very difficult task as the number of chemical threats of interest is very broad.

Low-Profile SCBA Cylinder Design

Over the last 10 years, there has been a push to redesign the concept of air cylinders. IAFF paved the way with their first attempt to develop a “flat pack” during the 2008 timeframe. The prototype system, developed in partnership with MSA, was able to reduce the profile, but did not significantly reduce the weight. This product did not become commercially available. Currently, Avon Protection is working in coordination with DoD to develop a confined-space SCBA with reduced profile and weight [83]. The product is intended to meet NFPA 1986 certification.

Conclusions

Hazard and risk assessments should be performed at all operational scenes. This information should drive the response considerations, especially as it relates to the implementation of engineering controls. PPE is the last line of defense to minimize exposure of hazards to the operator, but this must be balanced with operational effectiveness and thermal burden. The implementation of an effective PPE program, in concert with the hazard and risk assessment process, will maximize operator safety in the disaster response arena.

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