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A CB Protective Firefighter Turnout Suit

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This paper describes research that developed a prototype chemical and biological (CB) protective firefighter suit. It is presented as a case study demonstrating an integrated systems approach to designing, developing and evaluating a protective clothing ensemble based on end user requirements. It includes a discussion of the process that was used to gain an understanding of firefighter performance needs for a structural turnout suit that also incorporated chemical protection. It describes the design features of the turnout suit that were developed to meet these expectations as well as the program of testing and evaluation used to characterize garment performance. It discusses ensemble level performance evaluations in instrumented fire manikin tests and man-in-stimulant test procedures. It describes studies conducted to determine the impact of prototype garment design features on heat stress, wear comfort and ergonomic function in structural firefighting applications.

firefighter protective clothing   chemical protective clothing
protective clothing testing and evaluation

1. INTRODUCTION

Current firefighting ensembles provide protection against hazards in structural firefighting, i.e., radiant and conductive thermal exposures, flashover conditions, falling debris, and garment puncture and abrasion. Firefighters now face additional risks of chemical and biological exposures due to terrorism as well as exposures to toxic industrial chemicals (TICs) and toxic industrial materials (TIMs). Protective garments must meet these new requirements for protection against chemical and biological threats while at the same time minimizing heat stress and providing good ergonomic function.

The goal of this research was to develop and demonstrate a prototype firefighter suit that meets the requirements of thermal protection, while incorporating additional protection against chemical and biological agents. The chemical

The prototype CB turnout suit developed by this project is the product of an extensive, multi-faceted government supported research and development program that combined the efforts of researchers at NC State University, Globe Firefighter Suits, and input from firefighters. The authors gratefully acknowledge the Technical Support Working Group for providing support for this research. They express their sincere gratitude to the Fire Department of New York, Fairfax County Fire and Rescue, the Philadelphia Fire Department, the City of Raleigh Fire Department, and to the firefighters that facilitated and participated in the field and laboratory evaluations. They are also grateful to Globe Manufacturing for their invaluable contributions to this project. They wish to acknowledge the individual contributions of Mark Mordecai, Patricia Freeman and Robert Freeze of Globe Manufacturing.

Caveat. This paper describes technical elements involved in the development and evaluation of a prototype CB firefighter turnout system. Test data are presented for the purpose of characterizing the efficacy of garment design features that, when used in an integrated turnout system, provide levels of thermal protection and CB performance with clothing heat stress and ergonomic function consistent with the performance objectives of this project. The test results presented demonstrate performance characteristics of multiple prototypes and materials produced over the course of this research program. Laboratory testing cannot fully represent hazardous exposures encountered in actual firefighting or CB exposure events which can be physically complicated and subject to unforeseen conditions of use. This paper does not provide warranty or certification that turnout systems incorporating designs and clothing technologies developed by this research are suitable for particular commercial applications.

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and biological (CB) protective features were incorporated in a prototype design that demonstrates priority performance in a structural firefighting environment. This goal was viewed as crucial to achieving ultimate acceptance of the new turnout for use by firefighters.

2. DEFINING FIREFIGHTER NEEDS FOR A TURNOUT WITH CB PROTECTION

Input from firefighters was essential to enable development of a turnout with increased potential for ultimate acceptance and use for CB protection in structural firefighter gear. Therefore, the research team collected input from first responders with respect to their needs for the new garment. An approach was adapted that used a voice of the customer (VOC) exercise to obtain this information. The VOC approach is a systematic methodology that has been widely used by industry to assist new product development by obtaining focused information on user-stated expectations for product performance [1]. Our team developed a customized survey to obtain information about turnout use and performance requirements. This survey was distributed to first responders.

The survey was drafted following a careful review of the National Fire Protection Association (NFPA) 1971 and NFPA 1994 performance specifications, as well as the Project Responder Interim Report drafted after the Oklahoma City bombing, and the Rand Report Protecting Emergency Responders drafted after the 9/11 attack [2, 3, 4, 5]. Seventeen survey responders were selected from members of the NFPA 1971 and NFPA 1994 committee and from fire departments located in North Carolina, Virginia, Texas, and Delaware (USA). Participants also included individuals recommended by responders from these firefighter groups. After compiling the responses, first responders receiving the survey were invited to North Carolina State University (NCSU) to meet, discuss, and clarify their responses with the research team.

Key findings related to their expectations about garment performance can be summarized as follows:

- the new prototype turnout must be everyday turnout gear, first and foremost;
- the prototype must be designed for escape and rescue of viable victims;
- the turnout must have all equipment, required for protection, included on the garment at all times;
- the prototype turnout must be reliably donned without the use of a buddy;
- materials and garment design must not increase the level of firefighter heat stress; the prototype meet the performance requirements of the NFPA 1971 chemical, biological, radiological and nuclear (CBRN) option [2].

A significant amount of useful information related to performance expectations was obtained from the VOC survey and follow-up meetings with first responders. This information confirmed that reducing the heat stress associated with the current NFPA 1971 garment was of critical importance and that additional heat stress that may accompany extra protection would not be acceptable [2]. It indicated that protection against chemical vapors was a higher priority than protection against liquid chemicals, while indicating that protection against commonly occurring chemical vapors is a desired attribute of performance for a turnout suit with CB protection.

Survey results clearly showed that the firefighting community wanted and needed gear that would provide additional CB protection, but that they did not want their firefighting suit turned into a hazmat suit. They wanted this new suit to be turnout gear first, with everything on board needed to protect for short-duration escape and rescue and without increasing the heat stress during firefighter operations.

3. PROTOTYPE DEVELOPMENT PROCESS

An integrated systems approach was used to develop a series of prototype turnout systems. The concept motivated garment design solutions and embodied an approach that incorporates deployable features that provide first responders with an everyday structural firefighter suit similar to what is currently worn but is equipped with a deployable hood and a series of closures to provide additional CB protection, when needed.

The turnout system was designed for improved ergonomics, for fast donning, and with enhanced functionality versus current garment designs. The design approach optimized function and fit with an emphasis placed on the vapor integrity of seams, interfaces, and closures.

CB deployable design concepts were integrated into the turnout system that can be produced from the most advanced commercially available shell materials, and can incorporate two newly developed components—a high performance selectively permeable membrane and a lightweight thermal liner with excellent insulation. Outer shell fabrics were identified to provide lightweight, rugged protection from thermal and physical hazards.

A crucial aspect of the turnout development was identification of a suitable material for use as the moisture barrier, or CB barrier component, in the turnout suit. Moisture barriers, commonly used in conventional structural firefighter clothing, are required to resist the penetration of blood borne viruses, liquid water, battery acid, diesel fuel, and other corrosive chemicals. For NFPA 1971 standard compliance, they must also be resistant to heat, flame, and ultraviolet light, and possess a level of moisture vapor permeability for sweat evaporation [2]. The CBRN optional requirements of NFPA 1971 require the barrier to resist permeation exposure to nerve and blister agents. Permeation resistance must be demonstrated following conditioning procedures that exceed the severity of military preconditioning requirements for CB suits.

Selectively permeable membrane (SPM) technologies were identified as potential materials solutions to provide the level of CB resistance needed in addition to providing all the other functions of a conventional moisture barrier. SPM technology engineered for breathability and durable CB permeation resistance against a specific battery of agents and TICs is required to meet the CBRN optional requirements of NFPA 1971 [2].

This project conducted research aimed at optimizing the functional performance of the thermal liner component of the turnout prototype. This is an important materials development consideration, since a well-defined performance expectation was to reduce the weight and thickness of the turnout consistent with providing adequate thermal protective performance. Optimization of the thermal liner layer, therefore, presented opportunities to explore new fiber and fabric construction technologies with the objective of improving the low bulk thermal protective insulation of the turnout system. This research effort resulted in development of a lightweight thermal liner with excellent insulation and durability [6].

4. CB TURNOUT SYSTEM DESIGN FEATURES

Advanced materials were integrated into turnout suit prototypes that incorporated novel garment design features to provide thermal and vapor protection with improved human ergonomics and function for structural firefighting operations.

The CB prototype turnout suit (Figure 1) consists of a uniquely designed jacket and pants system with a CB protective hood integrated into the jacket collar. The turnout system is fitted with multiple innovative interface and closure systems to provide resistance to chemical vapor infiltration into the suit.

The turnout jacket assembly consists of separate inner and outer jacket components (Figure 2). These components are joined by a zipper across the top of the collar. The outer jacket component, fabricated from commercially available shell material, provides flame and abrasion resistance. The inner jacket component, fabricated from CB barrier material, is combined with the thermal liner system to provide liquid and chemical vapor protection and thermal protective insulation. The vapor integrity of the CB protective inner jacket component closure is provided by an integrated vapor and liquid resistant zipper. This zipper is offset from the

Figure 1. CB prototype.

Figure 2. Double jacket system.

front center of the inner jacket to permit full closure and sealing up the sides of the SCBA (self-contained breathing apparatus) mask.

The CB jacket consists of a draw string assembly fitted into an elasticized tunnel around the bottom hem of the inner jacket (Figure 3). This adjustable draw string is designed to be an easily deployable feature that can be used by the firefighter to snug up the inner jacket against the turnout pants for additional vapor resistance. Consistent with firefighter performance expectations, this deployable feature provides for a more relaxed and comfortable fit, or can be quickly tightened, as called for by operational requirements of firefighting.

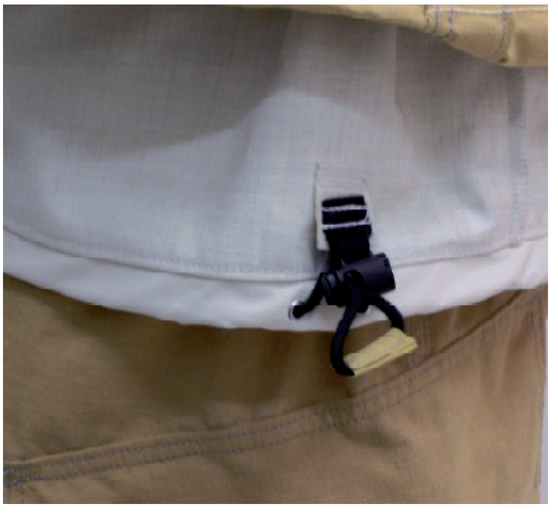

Figure 3. Adjustable drawstring.

The inner jacket also includes an elasticized back and a lacing system on the side that works like a pair of boxing gloves (Figure 4). When the adjustable lace system is deployed, the inner jacket tightly collapses against the torso to reduce air flow caused by movements. This, in turn, reduces the possibility of vapor infiltration into the suit system.

Figure 4. Adjustable lacing system.

A deployable CB protective hood is concealed in the collar of the jacket (Figure 5). The CB protective hood is typically deployed over a thermally resistant sock hood. It is designed to tighten around the SCBA mask when the inner jacket zipper is fully closed. The hood can be quickly deployed simply from the top of the jacket collar. This feature facilitates the action of pulling the CB hood up and over the head for easy deployment.

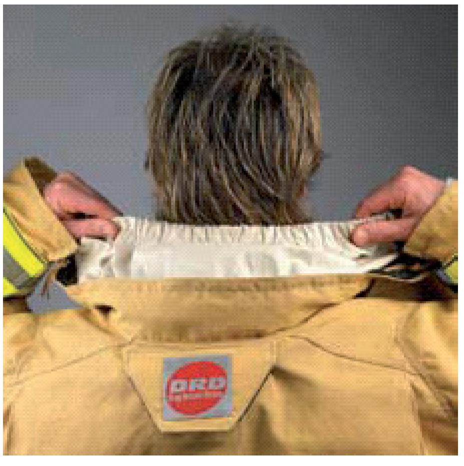

Figure 5. Zip away collar.

The vapor integrity of the interface between the turnout coat and gauntlet style gloves is provided by a series of closures on the glove and a novel design feature that uses motorcycle style zippers at the wrist area of the sleeve and around the glove (Figure 6).

Figure 6. Zip cuffs.

The turnout pants incorporate an extension above the waist which provides a gap-free closure between the jacket and pants whenever

Figure 7. SCBA (self-contained breathing apparatus) belt to pant interface.

the SCBA waist belt is tightened (Figure 7). The elasticized back and permanently attached belt helps transfer weight to the hips and away from the shoulders straps, adding vapor resistance at the top of the pants for added protection. This feature also controls the added length and fullness in the seat of the pants. The CB barrier is sewn directly to the outer shell around the perimeter of the pants only—waist, cuffs, and fly. Everywhere shell fabric can be seen there is a barrier fabric so that there are no gaps in protection. A large V-gusset behind the vertical Velcro® fly tucks out of the way when pants are donned and provides additional vapor protection (Figure 8).

The turnout pant has added length in the knee and the seat so that when the knee is bent, the pant does not ride up to strain the boot-pant interface. The pant cuffs incorporate a double water well closure to secure against the boot for additional vapor and splash protection. The pant cuff interface can be secured and pants pulled down over the top of boots so that the firefighter is always ready to step in and pull up pants.

One of the most challenging aspects of the turnout system development was associated with the need to provide an effective means of securing the double water well closure to the

Figure 8. Chemical and biological (CB) barrier gusseted storm fly.

Figure 9. Boot interface.

boots. Man-in-simulant test (MIST) results on an early project prototype system indicated that, because of boot flexing, vapor could infiltrate the suit at this critical interface. When the pant cuff was tightened around the boots, creases were created in the shaft of the boot. The tighter the pant cuff was secured, the greater the channels that allowed vapors and liquids to penetrate the suit. To correct this problem, a firefighter boot was modified for use with advanced prototype garments. These boots were designed to be light and flexible. Their CB performance relies on a CB barrier membrane on the interior of the boot. The innovation that provided additional vapor integrity, even when boots were flexed in walking, was an extruded collar attached around the boot shaft (Figure 9). By attaching the special collar around the boot shaft, creases were eliminated and a secure boot-cuff seal created.

The turnout suit incorporated many other constructional features designed to provide enhanced ergonomic function in firefighting, and greater range of body motion in wear. Ergonomic features constructed into the jacket include full-length expansion pleats on the outer jacket to provide unrestricted movement with or without a SCBA. Pleats and darts in the outer and inner jacket sleeve provide extra length when reaching. Curved sleeves in the turnout jacket follow the natural shape of the arm to provide decreased resistance when working.

5. PERFORMANCE TESTING AND EVALUATION

This project incorporated an extensive laboratory-based testing and evaluation program. Standardized materials level tests were conducted to characterize the thermal protective performance, liquid chemical and vapor resistance, and breathability of a variety of state-of-the-art turnout composites that were examined as materials for use in the construction of the CB turnout prototypes [7].

The following discussions will focus on the laboratory-based tests and procedures that were used to evaluate the turnout suit prototypes in the crucial areas of thermal, chemical, physiological and ergonomic functional performance. These evaluations were conducted during all stages of the project, and were designed to assess the feasibility of suit design concepts and validate the engineering of integrated turnout prototypes. These evaluations were conducted on full garments, and ensemble systems.

5.1. Thermal Protective Performance

The NCSU PyroMan instrumented fire test system was used to compare the thermal protective performance of a CB turnout prototype with a conventionally designed turnout system. The PyroMan test system permits an assessment of full ensemble thermal protective performance in laboratory simulations of fire environments, such as may be encountered by structural firefighters. These lab tests were conducted to determine if features of the CB prototype design reduced the predicted ensemble protection in comparison to a conventional, NFPA 1971 compliant, turnout system [2].

PyroMan tests were conducted on a CB prototype garment constructed with a turnout composite thermal protective performance (TPP) rating of 1 544 kW/m^2 (37 cal/cm^2) [8]. The conventional turnout control was constructed from composite with a TPP rating of 1 638 kW/m^2 (39 cal/cm^2). To recreate a worse case garment configuration scenario, the CB prototype test garment was mounted onto the fire test manikin without sealing the interfaces.

Figure 10 shows photographs of a CB prototype and control turnout before and after these turnouts had been exposed for 12 s to intense fire conditions (heat intensity of 84 kW/m^2 or 2 cal/cm^{2}s). Figure 11 provides a comparison of the predicted thermal protection provided by a CB prototype and control turnout systems.

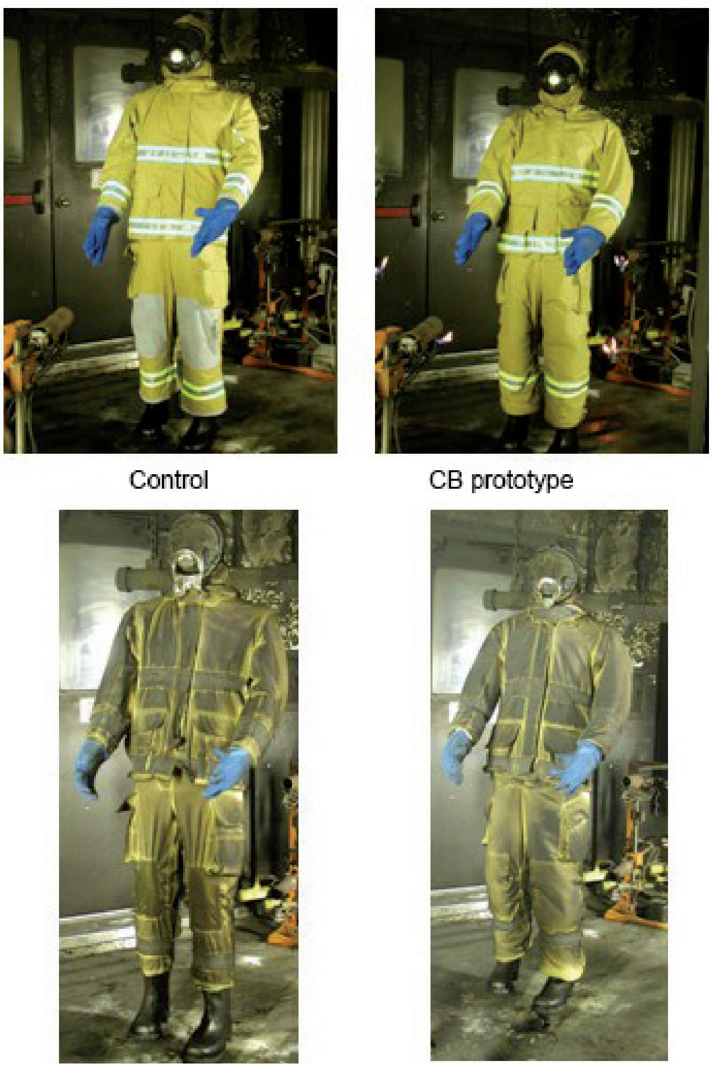

Figure 10. Chemical and biological (CB) and control turnout before and after PyroMan exposure (12-s exposure to average heat flux of 84 kW/m^2).

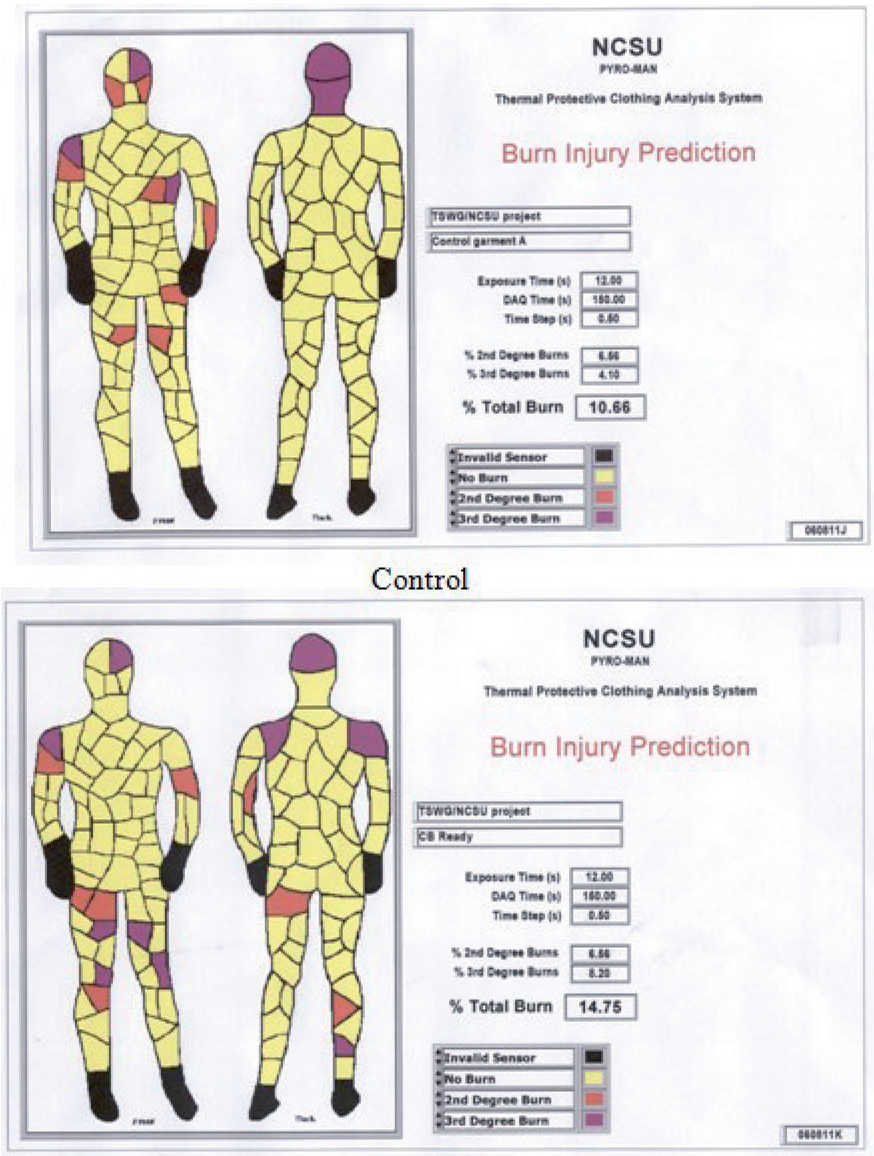

Figure 11. PyroMan burn injury prediction for chemical and biological (CB) and control turnout suits in 12-s exposure to average heat flux of 84 kW/m^2.

PyroMan test results showed a relative equivalence in the predicted fire protection between a CB turnout prototype and a conventionally configured system. These tests demonstrated the feasibility of incorporating CB design features without compromising the thermal protective performance of the turnout suit.

5.2. Chemical Protective Performance

MIST procedures provided critically important means of demonstrating the chemical vapor resistance of the turnout suit prototypes developed by this program. Project testing protocols followed procedures in the 2007 edition of the NFPA 1971 standard [2].

Using methyl salicylate (MeS) as the chemical agent vapor simulant for the blister agent, distilled mustard, the MIST evaluates the protective performance of a complete ensemble to resist chemical vapor penetration. MIST evaluates the inherent ability of materials and garment closure/interface designs to resist the penetration/permeation of the chemical vapor. Vapor penetration is monitored by passive adsorbent dosimeters (PADs; Syon ITW Devcon, USA) affixed directly to the skin of

Figure 12. Evaluation of chemical and biological (CB) turnout prototype in man-in-stimulant test (MIST).

the test subject in 30 locations across the body. Following application of the PADs, test subjects donned the test ensemble with respirator and proceeded to an environmental chamber with a prescribed wind speed and filled with a known concentration of MeS. Upon entering the test chamber, test subjects performed a protocol that included periods of physical activity alternating with periods of rest (Figure 12). Following the 30-min test exposure, subjects moved through specified decontamination and undress areas ending with removal of the PADs.

Shortly after removal, the PADs were analyzed for their MeS content. Further calculations yielded local physiological protective dosage factors and a systemic physiological protective dosage factor. PAD data were used in a body region hazard analysis to determine the overall physiological protective dosage factor accounting for the areas of the body represented by the location, and the relative effects of nerve agent infiltration. An assessment of the integrity for the entire ensemble was provided by the systemic physiological protective dosage factor. The systemic analysis assisted in the evaluation for those chemical agents, such as nerve agents, affecting the human body through a cumulative dose absorbed by the skin.

A series of MIST evaluations were conducted to assess prototype ensemble designs to determine the level of protection. These evaluations showed that the CB prototype, when compared to a conventional turnout garment, provided superior protection for areas of the body covered by the suit. Table 1 compares the systematic protection provided by the CB prototype and control turnout. These results demonstrated that the overall protection afforded by the prototype ensemble was over 40 times that of a conventional turnout ensemble. They showed that the CB prototype met the NFPA 1971 performance criteria for systematic chemical vapor protection [2]. They demonstrated that prototype deployable design concepts for closures and interfaces could provide enhanced resistance to chemical vapors.

TABLE 1. Comparison of Ensemble Resistance to Vapor Infiltration

Test Ensemble	Systemic PPDF
Conventional turnout	9
CB prototype	376

Notes. PPDF—physiological protective dosage factor, CB—chemical and biological.

5.3. Physiological and Human Factors Performance

An extensive series of laboratory-based studies were conducted to determine the impact of prototype CB design features on the potential for heat stress, wear comfort and ergonomic functionality in structural firefighting. This aspect of performance evaluation was considered a project priority in view of the stated firefighter expectation for CB protection incorporated into a turnout ensemble that would primarily function in conventional structural firefighting operations.

Firefighter turnout comfort, heat stress, and ergonomics are influenced by a complex combination of physical factors associated with the properties of materials used in the garment construction, by the fit and design of the turnout, and by the accessories and other gear worn or carried by the firefighter. Comfort is highly dependent on external environmental factors, including the temperature and humidity of firefighting environment, and by the specifics of the exertions and activities involved in the work functions of firefighters. NFPA 1971 [2] establishes a performance criterion for turnout composites based on the total heat loss (THL) measured using a guarded sweating hot plate test method [9]. Performance in this test is influenced by the heat and moisture vapor permeability of the fabric components in the turnout, especially the breathability of the moisture barrier component. This project addressed the materials contribution by identifying selectively permeable membrane technology as a category of materials having the potential to provide significant chemical barrier performance and breathability. The objective of laboratory evaluations, therefore, was to evaluate comfort and physiological factors at the ensemble level of the turnout prototypes developed by this project.

A combination of systematically designed laboratory assessments was used to assess comfort factors. Procedures included a sophisticated sweating instrumented manikin method, and extensive protocols that involved wear evaluations done by human subjects to determine the impact of the CB turnout on physiological and comfort.

5.3.1. Sweating instrumented manikin studies

A sweating manikin test was used to provide an instrumented measure of the effect of CB turnout designs on the heat loss from the body. The manikin consisted of several features designed to work together to evaluate clothing comfort and heat stress. Housed in a climate-controlled chamber, the manikin surface was divided into 18 separate sections, each of which had its own heating and temperature measuring system. With the exception of head, hands, and feet, the whole manikin surface could continuously sweat.

Water was supplied from a reservoir, which was located on a balance near the ceiling. An internal microvalve system distributed moisture to individually controlled “sweat glands”. Water supplied to each simulated sweat gland was controlled by the operator by setting the desired sweating rate. The manikin software algorithm used calibrated values to open each valve for the precise amount of time to deliver the desired amount of water. Although the head, hands and feet did not continuously sweat, prior to the sweat testing they were fitted with saturated fabric. This allowed for sweat simulation, albeit not as sophisticated as the continuous sweating that was possible throughout the rest of the body.

The sweating manikin test enabled an objective assessment of the effects of turnout composite breathability and suit design on predicted thermal burden of the turnout suit. Insulation measurements were conducted following Standard No. ASTM F1291-05 [10] while evaporative resistance measurements were conducted following Standard No. ASTM F2370-05 [11]. Both measurements were then used to calculate a THL value for the test ensemble.

The experimental strategy used to determine the impact of CB design elements on sweating manikin heat loss compared the CB prototype, with selectively permeable chemical membrane barrier with a conventional suit made from breathable composite materials. Both the CB composite and conventional composite were rated with similar THL values, greater than the 205 W/m^2 required by the NFPA 1971 standard [2]. Additionally, the CB turnout design was tested both with and without the CB closure systems engaged (Figure 13). This was done to permit an assessment of the effect of the CB deployable features of the suit on predicted heat loss from a sweating human body. Figure 14

Figure 13. Sweating manikin test of deployed prototype.

provides a graphical summary of these test results in environmental conditions controlled at 23 °C and 50% RH.

These comparative data indicated that incorporation of CB design features should have no significant impact on the thermal burden associated with body heat loss in these conditions. CB deployed features (sealed versus unsealed test suit) had little negative effect on the predicted breathability of the CB turnout prototype. However, these results were obtained on a static manikin test. The action of walking, and active movement in actual wear, could be expected to produce a somewhat different result. Human subject tests were expected to add significantly to the assessment of the thermal comfort of CB turnout design effects.

5.3.2. Physiological and subjective human subject wear studies

Systematically designed laboratory-based human subject wear trial protocols were conducted to determine the effect of CB turnout design elements on physiological factors associated with human heat stress in firefighter gear. A parallel study was conducted to assess CB design effects on subjective, or subject perceived, wear comfort associated with wearing a prototype CB turnout. The following discussion will focus on comparing the comfort performance of the prototype CB turnout with a conventional turnout suit. For this phase of the study, the CB turnout prototype was worn without deploying the garment level CB features. This permitted

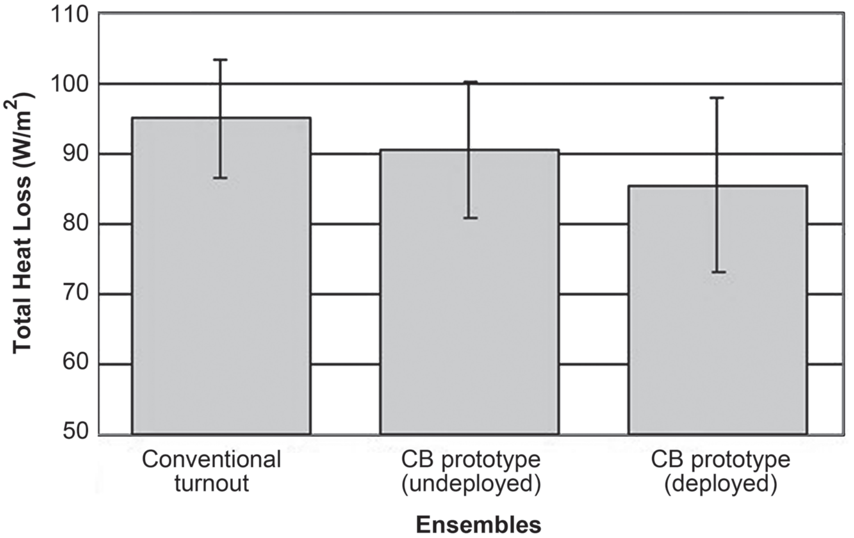

Figure 14. Comparison of total heat loss values from sweating manikin test of ensembles. *Notes.* CB—chemical and biological.

assessment of its performance in a configuration that represented the way it would be worn in routine structural firefighting operations. Detailed descriptions and results of studies conducted to evaluate the heat stress and comfort performance of the CB turnout prototype suit can be found in Light Weight CBRN Protective Fire Fighter Turnout [7] and Physiological, Comfort, and Ergonomic Evaluation of Firefighter Turnout and Hazmat Garments Phase 1 and 2 [12].

Wear trials procedures were conducted in a controlled environmental chamber and involved the participation of 8 male firefighters from the City of Raleigh Fire Department. Test garments were provided in a size specific to each evaluator. Evaluators donned the test garment over nylon running shorts with attached Coolmax® brief, cotton t-shirt, and crew length socks. A polybenzimidazole (PBI) knitted thermal hood, helmet, chemical mask, and SCBA harness equipped with a full tank completed the ensemble. Table 2 provides a summary of testing conditions and exercise regimen. Measured parameters in the physiological phase of these tests included heart rate, skin and core temperature, percentage of body fat, total body water, and garment weight before and after wear.

TABLE 2. Test Protocols Used in Chamber Wears for Physiological Assessment

Test Period	Time (min)	Structural Firefighting Protocol
1	15	rest: seated outside environmental chamber*
2	10	enter environmental chamber set to 31.1 °C, 50% RH; rest: seated
3	20	walk on level grade treadmill @ 4.3 km/h (2.7 mph)
4	15	rest: seated (mask and thermal hood off; jacket opened)
5	20	walk on 5% grade treadmill @ 4.3 km/h (2.7 mph)
6	10	rest: seated
7	20	exit chamber; rest: seated outside environmental chamber*

Notes. *—moderate room conditions of ~21 °C, 50% RH.

During the physiological wear evaluation, test subjects were asked to report their exertion using the standard rating of perceived exertion (RPE) scale in Table 3. Starting 5 min into the protocol, this rating was obtained every 10 min until the test ended. This is a measure to assess how hard subjects rate physical workloads imposed by each trial element.

Evaluators were asked to rank their perceived physical status in terms of comfort. The response form was designed to obtain ratings of comfort, fit, and functionality of the test garments. Using a 7-point bipolar scale, with a lowest value denoting the most desirable response, items on the evaluation form required subjects to rate the test garment on selected descriptor terms. These descriptors were stated negatively as it had been determined that individuals were better able to discern differences in degrees of unpleasantness rather than in degrees of pleasantness. Table 4 lists the descriptors with associated physical property or individual perceptions.

TABLE 3. Scale for Rating Perceived Exertion (RPE)

Rating	Description	Rating	Description
6	*very, very light*	14	
7		15	*hard*
8		16	
9	*very light*	17	*very hard*
10		18	
11	*fairly light*	19	*very, very hard*
12		20	
13	*somewhat hard*		

TABLE 4. List of Negative Descriptor Terms Contained in Response Form

Descriptor Term	Associated Physical Property or Perception
Overall comfort	sum of all, self-defined
Heat sensation	thermal feeling
Skin moistness	moisture management
Weight of garment	fabric structure, material selection
Flexibility	fabric stiffness
Remaining work time	physical workload

Table 5 shows that the average RPE value indicates an increase in perceived exertion that corresponds directly with the increase level of activity being performed in the protocol. During rest periods, the value chosen on the scale decreased. The perceived exertion level was slightly greater at the end of the test than that

TABLE 5. Average Rating Perceived Exertion (RPE) Ratings on Structural Firefighter Turnouts

Time (min)	Garment ID C	Garment ID UD
5	6.75	6.25
15	6.63	6.25
25	7.00	6.75
35	9.50	9.50
45	10.13	10.13
55	8.44	8.25
65	10.63	11.50
75	11.50	12.63
85	9.75	10.57
95	8.25	8.71
105	7.63	7.57
overall average	8.74	8.92

Notes. Lower values indicate low exertion levels are perceived; C—control, UD—undeployed.

recorded at the beginning of the test. However, these data do not indicate any significant differences in perceived exertion when wearing a conventional turnout (C; model GX-7; Globe Manufacturing, USA) and the CB prototype, worn in an undeployed configuration (UD), or without deploying the CB features designed into the suit.

Table 6 compares the subjective comfort ratings for the conventional turnout with rating received for the CB prototype turnout, worn without the CB features deployed. These data show that the comfort ratings varied for each garment according to the activity of the test period. The subjectively perceived comfort appears to be directly related to the level of physical exertion of the activities that are performed. In each case, ratings on all items were lowest, or more desirable, during periods 1–2, while sitting at rest prior to any physical activity. Ratings were highest (undesirable) following periods 5–6, after performing the second period of work and its corresponding rest session within the environmental chamber. After period 7, ratings fell toward the desirable end of the scale. However, in many cases, these ratings did not fall as low as those obtained in periods 1–2.

Figure 15 shows the combined ratings, averaged for seven periods. The conventional turnout (garment C) received more desirable ratings for overall comfort, heat sensation, skin

TABLE 6. Comfort Ratings for Control (C) and Chemical and Biological Prototype Turnout in Undeployed (UD) Wearing Configuration (n = 8)

Descriptor / Garment ID	Periods of the Firefighter Scenario Protocol 1	2	3	4	5	6	7	Combined Periods
Overall comfort								
C	2.25	2.25	3.63	3.38	4.25	4.00	3.00	3.25
UD	1.63	2.13	3.75	3.50	4.50	4.29	3.57	3.31
Heat sensation								
C	2.13	3.00	4.00	3.50	5.00	4.38	2.75	3.54
UD	1.88	2.75	4.13	4.00	5.38	5.29	3.57	3.82
Skin moistness								
C	1.00	1.63	3.88	4.25	5.13	4.50	2.88	3.32
UD	1.00	1.63	3.88	4.38	5.63	5.43	3.14	3.54
Weight of garment								
C	2.13	2.13	2.50	2.50	3.00	2.50	2.63	2.48
UD	1.63	1.75	2.38	2.13	2.50	2.71	2.29	2.14
Flexibility								
C	1.75	1.63	1.88	2.00	2.00	1.88	2.00	1.88
UD	1.50	1.50	1.88	1.88	1.88	2.14	2.14	1.80
Remaining work time								
C	1.13	1.13	1.88	2.13	3.63	3.75	3.50	2.45
UD	1.00	1.25	1.75	2.13	3.63	4.43	4.29	2.53

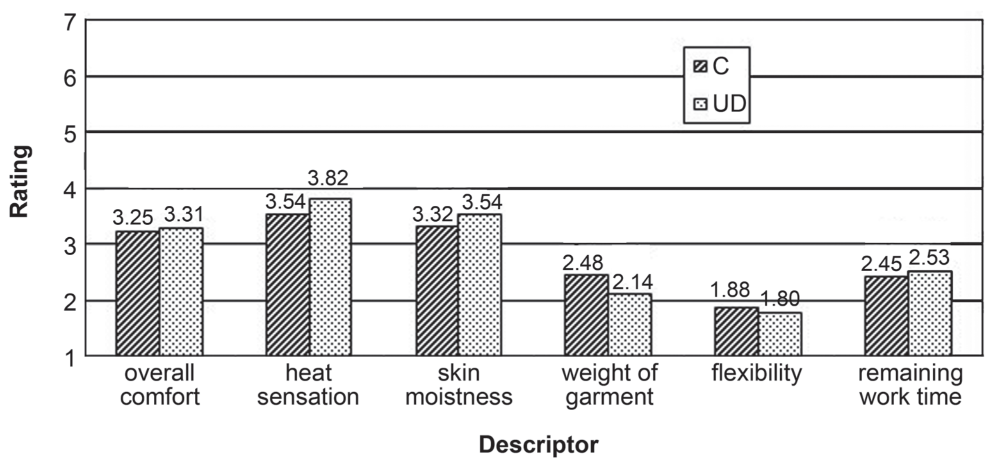

Figure 15. Average rating of comfort descriptors. *Notes*. Rating scale: 1—*desirable*, 7—*undesirable*; C—control, UD—undeployed.

moistness, and remaining work time. Ratings on flexibility and weight of garment were favorable to garment UD. Statistical analysis performed on the overall ratings showed there was no statistically significant difference on any of the comfort qualities rated.

5.3.3 Studies of ergonomic function

Priority was placed on assessing the effects of CB prototype design features on the ability of the suit design to function in routine firefighting operations. This was evaluated by using specially designed controlled laboratory tests to evaluate the ergonomic function of a CB prototype, configured both with and without deployable CB closure features in place during the test. The ergonomic protocols used were adapted from procedures specified in ASTM 1154-99a [13] and a candidate physical aptitude test (CPAT) used by fire departments in the U.S. for firefighter assessments [14].

The laboratory test protocol, summarized in Table 7, consisted of 8 professional firefighters

TABLE 7. Ergonomic Functional Utility Testing Protocol

Test Period	Time (min)	Activity (Exercise/Task)	Rate Difficulty Performing Exercise/Task	Rate Comfort Qualities
1	~15	don/doff garment 3× (1: show; 2: on own; 3: timed)	yes	no
2	~15	rest/instrumentation	no	no
3	~15	stair climbing (~50 steps/min)	yes	yes
		crawling (~65 ft[1])	after each	after completion
		ladder climb (1 min on VersaClimber, USA, with no resistance setting)	exercise/task	of all exercises/ tasks
		kneeling (4×: left, both right, stand)		
		box lifts (2–20 lb[2] each: floor–table 2×)		
		overhead/cross-body arm movements* (4×: raise arms overhead, bend, extend forward, bend, down. Followed by 4× of crossing arms around chest (self hug) and down)		
		uncoil and coil hose		
		dragging (165 lb[3] rescue dummy for ~90 ft[4])		
4	~10	timed exercise routine	no	yes

Notes. *—This activity was modified to accommodate an overhead arm movement during the timed routine. The overhead reaches were replaced with unscrewing two bars on a stair climber and placing on the floor. This was followed by simultaneously moving 2 weights, one for left hand and one for the right hand, to opposite sides four times. 1—~19.8m, 2—~0.9–9 kg, 3—~74.8 kg, 4—~27 kg.

performing a prescribed routine of physical activities, while wearing test ensembles. The ergonomic regimen was designed to simulate common firefighting activities in a controlled setting.

The ergonomic data enabled useful comparisons in performance between a CB turnout design and a conventionally configured turnout. Donning and doffing times of the deployed CB suit were found to be somewhat slower (Table 8), when compared to the control turnout. A significant difference was found between the donning and doffing times and ratings of getting into and out of the test suits. This was an expected result arising from test subject familiarity with the conventional turnout gear and their limited knowledge regarding use of the CB enhancements built into the prototype design.

Results of evaluator assessments of functionality, when job-related exercises and tasks were performed and turnouts were worn showed most were judged to be more difficult when the CB garment was worn (Table 9). The control turnout was slightly preferred when compared to the undeployed CB suit. This was an expected result due to test subject familiarity with the control suit. Regardless, the slight advantage of one garment over another was not statistically significant for any of the activities performed. Barker, Deaton, and Liston provide additional descriptions of the field and ergonomic evaluations [15].

5.3.4. Field evaluations

Characterizing firefighter response to CB turnout designs when deployed in field settings was an important part of the overall evaluation plan of this project. This project accomplished this task using evaluations in short field exercises conducted at selected firefighter training facilities. Exercises were carried out at three different major metropolitan fire departments:

TABLE 8. Donning and Doffing Times and Ratings (n = 6)

	Turnout Type		
Activity/Firefighter Rating	**Conventional**	**CB Undeployed**	**CB Deployed**
Donning time (s)	71	94	196
Doffing time (s)	30	36	55
Ease of “getting into”*	1.4	4.6	5.4
Ease of “getting out of”*	1.4	3.7	4.6
Routine time (s)	361	391	380

Notes. *1—*extremely easy*, 5—*extremely difficult*; CB—chemical and biological.

TABLE 9. Difficulty Ratings of Exercises and Tasks

	Turnout Type		
Activity	**Conventional**	**CB Undeployed**	**CB Deployed**
Stair climb	1.9	1.9	2.1
Crawling	1.9	1.8	2.3
Ladder climbing	2.5	2.6	3.1
Kneeling	1.9	1.8	2.3
Box lifts	1.6	2.1	1.9
Overhead arm and cross body	1.4	1.6	1.8
Hose uncoil and coil	2.4	2.4	2.8
Dragging	3.8	3.9	3.9
overall rating	2.2	2.3	2.5

Notes. 1—*extremely easy,* 5—*extremely difficult*; CB—chemical and biological.

the Fire Department of New York (FDNY), Fairfax County Fire and Rescue, and the Philadelphia Fire Department. A total of 18 firefighters participated at these three test sites. These evaluations were not extended field trials. The objective was to obtain firefighter response to the CB features incorporated into project turnout prototype with respect to their perceived utility in a turnout suit to be used for both routine firefighter activities and in escape and rescue activities in a CB incident.

Evaluation protocols enabled CB design features to be evaluated by professional firefighters while they were wearing prototype turnout suits along with a full complement of structural firefighting gear, including appropriate SCBA equipment, hood, boots, and gloves. The evaluations occurred as the firefighter participants performed prescribed regimens of physical activities. The specifics of the activity routines were tailored for each fire department test site.

The regimens used at the Fairfax and Philadelphia Fire Departments were based on activities called for by their respective firefighter CPAT routines. These activities permitted assessment of the turnout impact on walking, carrying heavy objects, dummy dragging, and on hose, hammer and ladder work. For example, The FDNY test included the following activities: climbing, forced door entry using a Halligan tool and axe, operation of a saw, hose and Hurst tool, dummy drag, and deployment of a system used for exiting and descending from a window (Figure 16).

The evaluations of the CB turnout design were based on obtaining qualitative descriptions of the perceived or the potential effects of the test turnout system on task performance, wear comfort, and on practicality for use in structural firefighting or for deployment in escape and rescue. In addition, systematically designed questionnaires were used to obtain quantitative data in these same critical categories of performance. Table 10 shows a summary of the quantitative results on performance ratings.

The results from these exercises can be summarized as follows: firefighter ratings and comments show that the CB turnout deployable design features can be expected to have minimal negative impact on factors related to performing the physical tasks typically associated with structural firefighting operations. The CB suit design received generally high marks for comfort, ease of motion, and deployment. They can be donned in about the same time as a conventional turnout system. These results indicate that firefighters can accept the basic CB suit design concepts for use as structural firefighting gear.

Fairfax New York Philadelphia

Figure 16. Fire department evaluations of chemical and biological (CB) prototype turnout.

TABLE 10. Average Performance Rating of Prototype CB Turnout Suit (*n* = 6)

Question	New York, NY	Fairfax, VA	Philadelphia, PA	Overall
CBRN performance				
Importance of CB protection?	2.8	3.5	4.0	
Deploy for escape and rescue?	3.3	3.8	3.3	
Deploy in a timely manner?	2.2	3.7	3.2	
Practicality of deployment?	3.2	4.0	3.7	
section average	2.9	3.8	3.6	3.4
Structural firefighting performance				
Perform as expect a turnout?	3.1	3.7	3.6	
Complete all tasks?	4.0	3.9	4.0	
Degree of mobility and flexibility?	3.8	4.0	3.9	
How comfortable?	3.0	3.9	3.7	
Appearance?	3.0	4.0	3.8	
Practicality for everyday use?	2.7	3.9	3.5	
section average	3.3	3.9	3.8	3.7
Overall rating				
Overall impression	2.8	4.0	3.7	3.5
evaluation average	3.1	3.9	3.7	3.6

Notes. 4—*very*, 3—*likely* or *somewhat*, 2—*not very*, 1—*not at all*; CB—chemical and biological, CBRN—chemical, biological, radiological and nuclear.

6. CONCLUSIONS

A prototype fire fighter turnout system was developed to meet the multithreat environment facing the fire fighting community. The new garment was designed to meet NFPA 1971 thermal requirements while providing protection from CB agents, and a range of TICs and TIMs. The turnout suit was engineered for CB protective performance with improved ergonomics, fast donning, and enhanced functionality versus current turnout garment designs. The design approach optimized function and fit with emphasis placed on the vapor integrity of seams, interfaces, and closures. The turnout system can be produced from the most advanced commercially available shell material and can incorporate two newly developed components—a high performance selectively permeable membrane and a lightweight thermal liner with excellent insulation. Performance of the composite materials was evaluated through extensive laboratory testing against key requirements. The performance of the whole turnout system was assessed through manikin tests for thermal protection and for heat stress and breathability. Enhanced protection against infiltration of chemical vapors was demonstrated in MIST. The ergonomics, functional utility for structural firefighting, and physiological aspects were qualified in controlled laboratory settings and in field evaluations.

This project has advanced the science and technology of materials and garment designs for firefighter turnouts. In so doing, it contributed to a technical knowledge base that was useful in the development of an NFPA standard [2] that includes optional performance requirements for CBRN protection for structural firefighter protective gear. It has demonstrated the value of incorporating firefighter input in all phases of the prototype development.

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