

ABSTRACT

MCQUERRY, MEREDITH LAINE. Clothing Modifications for Heat Strain Reduction in Structural Firefighter Protective Clothing Systems. (Under the direction of Dr. Roger L. Barker and Dr. Emiel A. DenHartog).

The profession of firefighting is one of the most dangerous occupations in the world. Firefighting results in an average of 80,000 occupational injuries per year, over half of which are due to heat stress and cardiovascular strain. Protection requirements often contradict the need for heat dissipation, leading to excessive clothing insulation which creates a negative impact on wearer comfort between 80-90% of a firefighter's working time. The purpose of this research was to investigate clothing design modifications for their ability to reduce the heat strain experienced by firefighters. Four garment level design modifications including: ventilation openings, layering effects, systems modularity, and air gap volume reduction were initially explored in separate experimental studies to determine their heat loss potential in structural firefighter turnout suits (turnouts). Passive and active vent designs, removal and rearrangement of fabric and clothing layers, and tighter fitting materials were implemented on the garment level.

Each design modification was evaluated on the garment level using a sweating thermal manikin to gather thermal insulation (dry heat loss) and evaporative resistance (wet heat loss) measurements in multiple test conditions (standing with still air, walking with still air, standing with wind, and walking with wind). A predicted manikin total heat loss (THL) value was calculated for each turnout with a design modification and compared to a standard control turnout with no modifications. Virtual human thermal modeling was conducted to predict the wearer's physiological responses (core temperature, skin temperature, and sweat rate) when wearing turnouts with each of the design modifications under a specified protocol

indicative of a realistic vehicle extrication scenario. Predictive modeling data from this method was used to further inform the product development process of turnout prototypes with improved comfort performance properties.

Design modifications which showed significant improvements in heat loss and predicted physiological comfort were implemented into structural firefighter turnout prototypes. Initial results demonstrated significant increases in heat loss and meaningful improvements in physiological comfort for the active ventilation designs, modular systems approach, and reduced air gap volume.

Using the functional design process, a total of four different structural turnout prototypes were developed including: a modular single layer outer shell system (USAR), an active vent zipper turnout (Venting), an athletic fit tapered suit with breathable stretch materials (Stretch), and a combination suit with venting, stretch materials, and reduced thermal liner layers (Revolutionary). Manikin THL and predicted physiological responses were analyzed for each prototype suit in a 35°C/35% relative humidity environment for 100 minutes. Initial results indicated improved physiological comfort for the USAR, Venting, and Revolutionary prototypes.

A full systems human wear trial was conducted using eight subjects from local Raleigh fire departments. Physiological response data from the wear trial demonstrated significant improvements in lowered core temperature, skin temperature, and physiological strain index (PSI) when wearing the USAR, Venting, and Revolutionary prototypes compared to the Control turnout. There were no benefits for improved heat loss or physiological comfort when wearing the Stretch prototype.

Conclusions from this research established a significant relationship between measured THL values on a sweating thermal manikin and corresponding realized improvements in physiological comfort for the firefighter. In addition, it validated the use of human thermal modeling as a down selection tool in the product development process.

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Clothing Modifications for Heat Strain Reduction in Structural Firefighter Protective
Clothing Systems

by
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DEDICATION

To those I lost along this journey:

To my grandfather for being the patriarch of our family which instilled in me, from the beginning, my foundation of faith without which I would have surely given up long ago. To Mark, Janet, and Colin, my second family. Your strength, courage, and faith through trials and tribulations inspires me and gives me strength to continue this journey called life.

BIOGRAPHY

Meredith Laine McQuerry (Cinnamon) was born September 12, 1990 to Dale and Joan Cinnamon in Salvisa, Kentucky. She has a younger brother, Clay Cinnamon. Meredith lived in Salvisa throughout her childhood and graduated from Mercer County Senior High School in 2008.

Following high school, she moved to Lexington, Kentucky to attend the University of Kentucky (UK) double majoring in Family and Consumer Science (FCS) Education and Merchandising, Apparel, and Textiles (MAT). During her undergraduate career she was a member of PHI U (the national honor society in FCS), the American Association of FCS, and served as President of the MAT Club and Educators of FCS. She was an ambassador to the College of Agriculture, a peer-instructor for freshmen orientation courses, and the coordinator of the Cotton Incorporated Denim Drive. She also served on the UK Official Plaid Advisory Board as the student representative and member of the product development committee. As a sophomore, she began working in the Textile Testing Lab as an undergraduate research assistant, eventually becoming the senior lab technician and lab supervisor. She was recognized as the undergraduate student of excellence in both degree programs and as the undergraduate student of distinction, the highest award given to undergraduates in the School of Human Environmental Sciences. In 2012, after completing a semester of student teaching, she graduated first in her class out of 2,000 students in the College of Agriculture.

Meredith was fortunate to have the opportunity to continue her research at UK in the area of structural firefighter turnout durability through the pursuit of a Master of Science

degree in MAT, with an emphasis in Textile Science. During her graduate studies at UK she earned her Six Sigma green belt, received first place in the American Association of Textile Colorists and Chemists (AATCC) Herman and Myrtle Student Paper Competition, and presented her thesis internationally. She was also provided the opportunity to travel abroad in Paris, London, and Scotland. The culmination of her thesis led to multiple conference presentations, a publication in Fire Technology, and the first place award in the American Society of Testing and Materials (ASTM) student paper competition. At the conclusion of her Masters she was blessed to finally marry her high school sweetheart Travis McQuerry.

Upon completion of her Master's degree, Meredith pursued her Ph.D. in Textile Technology Management at North Carolina State University beginning in 2014. She worked closely with those in the Textile Protection and Comfort Center (TPACC) to study the physiological burden of structural firefighter turnouts on firefighter comfort. This work was published in the Textile Research Journal, AATCC Journal of Research, ASTM Selected Technical Papers, and Fire Engineering. During her Ph.D. Meredith completed the Mentoring and Teaching Practicum Program, taught as an adjunct professor at Meredith College, and was part of the 2015 Building Future Faculty cohort.

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1 Introduction

The field of firefighting is one of the most dangerous occupations in the world. Firefighting results in an average of 80,000 occupational injuries per year, with half of those occurring on the fire ground, where the fire is actively being fought (Park, Rosengren, Horn, Smith, & Hsiao-Weckslar, 2011). Firefighters face numerous hazards, especially those of heat, flame, and high temperature exposure. Other concerns include liquid protection (from water and steam), chemical protection (from carcinogen causing contaminants), trips and falls, impact penetration resistance (to avoid punctures from sharp objects), and fatigue. While the majority of these hazards come from the external environment, others are a direct or indirect result of the portable clothing environment.

Protection requirements of structural firefighter turnouts often contradict the need for comfort. Improvements in thermal protection have been created by adding multiple fabric layers to the turnout ensemble which increases the weight and decreases air and moisture transfer necessary for heat loss (Rossi, 2001). Additional thickness and garment bulk add to the amount of energy expended during physical activity and reduce the time to fatigue (Duggan, 1988). An increase in garment weight and bulk makes heat dissipation more difficult and leads to a greater risk of overheating (Duggan, 1988).

The human body is constantly working to achieve thermal homeostasis in which a balance between heat production and heat dissipation is required (Ingvar Holmér, 2006). When restrictions to heat transfer are imposed, such as heavier and bulkier garments, physical work requires more energy and produces greater metabolic heat (Ingvar Holmér,

2006). For the body to maintain thermal homeostasis it must dispel the gain in metabolic heat. Clothing layers create both thermal and evaporative heat resistance, further hindering heat loss. The inability of the body to maintain its proper heat balance will lead to heat illnesses such as fatigue, exhaustion, and stroke. To reduce the risk of heat stress, and improve the physiological comfort of structural firefighter turnout garments, more research to improve heat loss needs to be conducted.

Therefore, this research investigated clothing modification concepts for heat loss improvement to reduce the risk of physiological heat strain for firefighters wearing structural turnout clothing ensembles. Four individual design modification concepts were evaluated including: garment ventilation, strategic reduction of fabric layering, systems modularity, and air gap volume reduction.

This research was conducted in two phases. The first phase included individual experimental studies for each of the four design modifications on both the fabric and garment level to determine the heat loss reduction capability of each concept. The second phase involved down selecting concepts, given the outcomes from the first phase, to develop more advanced turnout prototypes. In this phase, a human subject wear trial was conducted to determine the physiological impact of the designed turnout prototypes on reducing heat strain when implemented in structural turnout prototypes. As a bridge between manikin level evaluations and human wear trial measurements, virtual human thermal modeling was used to predict the physiological responses of each design modification to help inform product development design decisions for the prototypes.

1.1 Purpose of Research

The goal of this research was to study the effects of clothing modifications, including selective layering, air gap volume, and garment ventilation, for the purpose of increased heat loss which may lead to reduced physiological heat strain in structural firefighter protective clothing. This research study established a relationship between the heat loss properties of clothing modifications and their ability to effectively reduce heat strain for the wearer.

1.2 Research Objectives

The overarching objective of this research was to investigate clothing modification concepts such as, clothing ventilation, strategic composite layering, and reduced air gap volume for heat loss improvement, in structural firefighter turnouts. By evaluating design concepts in realistic conditions, through predicted modeling and measured physiological heat strain responses, it is possible to establish a benchmark for the amount of heat loss necessary to produce a significant reduction in heat strain.

To achieve the purpose of this study, the following objectives were established:

1. To investigate optimal clothing modifications, in structural firefighter protective clothing systems, for heat strain reduction.
 - a. To analyze clothing ventilation, layering effects, modularity, and air gap volume for their influence on heat loss in structural firefighter turnouts.
 - b. To determine how additional fabric reinforcements and clothing layers influence heat transfer, on both the fabric and garment levels, in structural firefighter clothing ensembles.

2. To establish a relationship between the heat loss capabilities of structural turnout garments, with various optimal clothing modifications, and changes in physiological heat strain for the wearer.
 - a. To establish a benchmark for the amount of heat loss necessary to achieve a meaningful impact for improved physiological comfort.
 - b. To determine the correlation between predicted physiological responses and measured responses on human subjects as a method for validating the human thermal model.

Achievement of these objectives provides future designers, manufacturers, and researchers with valuable knowledge of the heat loss requirements for structural firefighter turnouts in order to reduce the risk of heat strain and lessen the number of heat illness incidents. Furthermore, it will provide clothing physiologists with a greater understanding of the effects of clothing ventilation, composite layering, and air gap volume on heat transfer and clothing insulation in protective clothing systems.

2 A Review of Garment Ventilation Strategies for Structural Firefighter Protective Clothing

2.1 Introduction

Structural firefighter turnouts are designed to provide protection against fire and thermal hazards. They must also protect the firefighter from liquids from the fire ground and blood borne pathogens. The protective aspect of clothing in general, also creates an air layer between the skin and the clothing, which is denoted the '*microclimate*'. As modern turnouts have become increasingly encapsulating, the microclimate becomes close to the temperature and humidity at the human skin, there has been corresponding interest in developing designs that provide enhanced heat loss from the microclimate to reduce the heat strain. Approaches can include more air permeable turnout materials and open garment designs. One heat strain reducing garment strategy that can be considered to improve heat loss is the incorporation of ventilation into the turnout. The functional theory of garment ventilation is based on the assumption that vents enhance body heat loss to the environment primarily by enabling convective and evaporative heat transfer through the clothing or by venting microclimate air via openings ('vents') in the suit that allow direct air exchange between the microclimate and the environment. The incorporation of vents into turnouts is particularly challenging since any heat strain reduction that is realized must be accomplished without compromising the fundamental need to provide protection against thermal, liquid and toxic environmental hazards.

While the concept of using vents in functional clothing to increase air exchange and heat loss is well known, there are relatively few studies specifically addressing ventilation

approaches and effects in structural firefighter gear. Additional literature sources can be found that apply ventilation concepts to other types of functional clothing, particularly clothing designed for outdoor and sports applications. This chapter, therefore, will provide a review of ventilation in structural firefighter turnout clothing. It will discuss findings from studies of ventilation in other types of protective and active wear clothing. This review is designed to be a useful source of information of value to researchers seeking to design and incorporate ventilation features into firefighter turnout designs.

2.1.1 Heat Strain in Protective Clothing

Humans are homoeothermic, which means they require a balance between the amount of heat produced by the body and the amount of heat the body loses to the environment (Bouskill, 1999; Reischl & Stransky, 1980a; Watkins, 1984). Protective clothing hinders heat loss as it often consists of multiple fabric layers for protection against puncture, chemicals, heat and flame, steam, and gases (Reischl & Stransky, 1980a). When multiple layers of clothing are worn the air and moisture exchange from the body to the environment is reduced. For workers who operate in warm environments or who perform heavy physical activity, heat strain may occur as a result of the personal protective clothing being worn (Dukes-Dobos, Reischl, Buller, Thomas, & Bernard, 1992). For firefighters, thermal protection is of utmost importance, however, a contradiction occurs between the necessary thermal protection required and the need for heat loss (Bouskill, 1999).

2.1.2 Heat Loss through Protective Clothing

The body's primary mechanism for removing excess heat is through sweat evaporation, which is reduced by high humidity and lack of air movement when clothing is

worn (Dukes-Dobos et al., 1992; Reischl & Stransky, 1980b). When the body performs physical activity it produces heat which must escape from the body in order to maintain a balanced core temperature. If this heat cannot escape, heat strain, fatigue, stroke, and even death may occur for the wearer. The addition of clothing, especially multiple layers, creates air gaps which further hinder the ability of sweat to evaporate to the outward environment. Humid conditions also play a role in reducing sweat evaporation as well, along with the type of fabric and material of the clothing.

Convection is the transfer of mass and heat by a gas or liquid, or in this application, air exchange (Watkins, 1984). In order to increase heat loss through convection, the ambient air temperature must be less than the microclimate air temperature within the suit. The greater the difference between the two gases, or air temperatures, the greater the heat exchange (Watkins, 1984). There are two types of convection: natural convection, which occurs due to existing temperature gradients, and forced convection which occurs with air movement, due to wind or 'pumping', due to human activity. As a baseline, garments are often tested in a dry environment, with no wind and no movement. This eliminates the effects of pumping when the body is moving, such as walking, and forced convection effects when wind is present (Ruckman, Murray, & Choi, 1998).

Pumping or bellows ventilation is defined as a mechanism of air exchange which results from rhythmical movements of the limbs and body during physical activity (Vokac, Kopke, & Keul, 1973). This effect occurs as movement forces air around clothing and brings air in or pushes it out through openings (Dai & Havenith, 2009). These openings can be of traditional design such as the collar, cuffs, and bottom hems or they can be purposefully

designed as vents. Pumping is simulated in manikin testing by making the manikin perform a walking motion.

The second type of heat loss which occurs within the clothing system is evaporation of sweat, which is an "extremely effective" tool for heat transfer (Watkins, 1984). This type of heat loss is a last resort for the body when heat cannot be properly removed through convection (Smith & Havenith, 2010; Watkins, 1984). Even in low temperature environments, with the addition of protective clothing, the body may rely heavily on sweat evaporation in order to prevent overheating (Smith & Havenith, 2010). Only at very low work rates would the wearer not sweat as the amount of heat loss by sweat evaporation increases as the metabolic rate rises (Birnbaum & Crockford, 1978). This concept is illustrated in Figure 2-1 below.

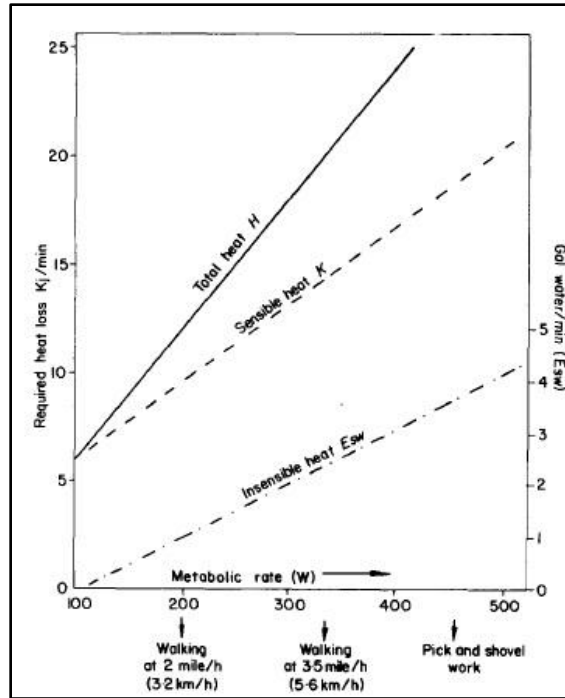


Figure 2-1. Sensible and evaporative heat losses for comfort related to metabolic rate (Birnbaum & Crockford, 1978).

In hot and humid environments the need for sweat evaporation is even greater. The body's available cooling power through sweat evaporation is not only dependent upon the environmental conditions, but the fitness level of the individual, the state of acclimation of the body, the type of clothing being worn, as well as the evaporative efficiency of the clothing materials (Smith & Havenith, 2010). One way to impart change and increase sweat evaporation in the clothing system, beyond improving materials, is to increase the rate of air exchange between the clothing ensemble and the outer environment (X H Zhang, Li, & Wang, 2012). Air exchange between a specific location within a garment and the environment involves three parts which include: 1) air exchange between local body parts'

microclimates, 2) air exchange through the fabric layers to the environment, and 3) air exchange through garment apertures with the environment (Ke, Li, & Havenith, 2014). Of these interactions, the most effective for heat loss is air exchange between the microclimate and the environment through garment apertures (Ke et al., 2014).

2.1.3 Ventilation in Clothing to Increase Heat Loss

In order to alleviate the buildup of heat within the clothing system, ventilation may be employed. Ventilation is defined as, "the amount of ambient air that flows under the garment after passing through the fabric and/or through (designed) openings," (Dukes-Dobos et al., 1992). The presence of ventilation features within a clothing system has the potential to remove excess body heat and reduce the discomfort caused by excess sweat (Ruckman et al., 1998). These ventilation features allow for sweat and heat to escape more easily from the microclimate and away from the wearer's skin. For protective clothing, garment design improvements and fabrication changes are necessary to increase the amount of heat loss while maintaining protection (Reischl, Stransky, Delorme, & Travis, 1982). These design improvements have shown measurable differences in skin temperature during physical activity on human subjects (Reischl et al., 1982). For prototype structural firefighter turnouts, garments which incorporated both ventilation openings and fabrication changes had the lowest recorded skin temperature and greatest ventilation, as measured by temperature differences compared to standard control turnouts. As Watkins describes in *Clothing The Portable Environment*, design openings in the arms, waistline, and cuffs, along with a spacer placed between the skin and first layer of clothing, may be added to increase the ventilation in protective clothing (Watkins, 1984).

To determine if ventilation is a viable approach for increasing heat loss, an understanding of heat transfer, convection, and evaporation is necessary. Dai and Havenith evaluated this relationship by measuring the local ventilation of the clothing microenvironment, thermal insulation, and evaporative resistance in various air movement conditions and by making the manikin stand and walk (Dai & Havenith, 2009). This study involved the use of a trace gas dilution method to measure localized ventilation in two jackets while the manikin was standing still and while walking in wind speeds of 0.4 and 2 m/s (Dai & Havenith, 2009). During natural convection, when the manikin is stationary and there is no wind, the ventilation was the lowest among all of the tests. The only air exchange which occurs in this condition is the permeation through the fabric of the jackets. With the addition of walking, pumping effects can be seen as the ventilation increased by over 100% for both jackets evaluated (Dai & Havenith, 2009). Forced convection, through increased wind speed, was found to contribute more to ventilation than pumping. Jacket A ventilation increased by over 800% with forced convection alone (Dai & Havenith, 2009). Heat transfer increased as both the wind speed and body walking were introduced. The conclusion of this study was that clothing ventilation affects evaporative resistance more so than thermal insulation (Dai & Havenith, 2009). The heat and moisture transfer within a clothing ensemble is affected not only by the specific materials used but also by the design of the garment, including the style, size, fit, and added accessories (Li, Barker, & Deaton, 2007).

The addition of a ventilation spacer placed between the skin and the first layer of clothing have been suggested by Watkins (1984) and evaluated by Reischl and Stransky (Reischl & Stransky, 1980a). However, this evaluation was done in conjunction with various

other types of ventilation within the same firefighter turnout. Future research should evaluate ventilation designs separately, including microclimate spacers placed within the turnout. If cold and/or dry air moves into the microclimate of a clothing system it will act as a "heat sink" and mix with the warmer air that is present in the microclimate (Bouskill, 1999) leading to heat loss when exchanged with the environment . However, if hot air moves into these layers, it causes an increase in temperature of the microclimate air, leading to an increase in skin temperature (Bouskill, 1999). This may cause discomfort for the wearer and prolonged exposure to this condition may lead to additional thermal strain due to the imbalance of heat transfer from the body (Bouskill, 1999). Very little experimental data is available on this issue, but the general trend warrants concern, so any microclimate ventilation system should address this issue and incorporate design features to allow for a reduction of ventilation under very hot conditions.

2.2 Clothing Ventilation Measurement Methods

To measure whether or not ventilation has a benefit towards heat loss, methods using a sweating manikin or trace gas dilution technique should be used. A sweating manikin measures the thermal insulation and evaporative resistance of garments. Thermal insulation can be defined as, "the resistance to dry heat transfer by way of conduction, convection, and radiation," (ASTM, 2010b). Evaporative resistance is, "the resistance to evaporative heat transfer from the body to the environment," (ASTM, 2010a). From these measurements, a predicted Total Heat Loss (THL) value can be calculated for the overall garment. The trace gas dilution method, can be used to measure the ventilation index of the garment. The ventilation index is calculated from the measure of the micro-environment volume and the

tracer gas rate of air exchange (Birnbaum & Crockford, 1978). This index describes the air exchange characteristics of a garment and can be used to rate the performance of protective clothing ensembles (Birnbaum & Crockford, 1978). This method is more complicated than the sweating manikin but can be completed in a shorter amount of time. To the authors' knowledge no clear direct comparison between results from the sweating thermal manikin THL method and the direct ventilation method have been made yet. Finally, thermo-regulation models may be used to evaluate the effect of ventilation in various environmental conditions and real-life scenarios that firefighters would encounter. Each of these methods will be discussed in detail below.

2.2.1 Total Heat Loss (THL) using a Sweating Thermal Manikin

Evaluating ventilation on the manikin level allows for the entire clothing ensemble to be assessed, including pockets, accessories, boots, gloves, hood, and helmet. This method takes into account the amount of body surface area covered by different materials and various numbers of layers, the fit of the garment, and the increased surface area for heat loss (Ross, Barker, & Deaton, 2012; Walker, 2013). The sweating manikin includes separately controlled heated sections with built in pores for sweating (Measurement Technology Northwest, 2007). A typical sweating manikin that is often used contains a fluid pre-heater inside the manikin to ensure the water coming through the pores is maintained at the proper temperature, according to the standard test methods. The manikin is connected to a computer software program which monitors the heaters, fluid temperature, and flow set points for each section (Walker, 2013). This allows for an evaluation of dry air exchange (thermal resistance) and wet moist vapor exchange (evaporative resistance).

Thermal resistance is tested in accordance with ASTM F1291-10 *Standard Test Method for Measuring the Thermal Insulation of Clothing Using a Heated Manikin* which determines the insulation value of a clothing ensemble (ASTM, 2010b). ASTM F1291 provides the measurement of resistance to dry heat transfer from a heated manikin to a relatively calm, cool environment (ASTM, 2010b). Dry heat loss measurements are computed into thermal resistance values for the ensemble. Measurements should be taken on the ensemble prior to adding vents and once ventilation is in place to compare the effect of ventilation on heat loss.

To measure evaporative heat loss ASTM F2370-10 *Standard Test Method for Measuring the Evaporative Resistance of Clothing Using a Sweating Manikin* is used. The manikin and environmental temperatures are the same (35°C) to ensure there is no dry heat transfer occurring as well (ASTM, 2010a). Evaporative resistance measurements can be combined with thermal resistance measurements to determine the overall predicted THL for the suit when ventilation is added.

THL of the full clothing ensemble can be determined based upon the thermal and evaporative resistance measurements. It is an effective measure for estimating the overall ventilation effect on heat loss throughout the garment. The measurements taken from the sweating manikin will provide the most comprehensive data for evaluating the benefit of ventilation to reduce heat strain in clothing. The type of heat loss (dry or wet) can be compared, along with the effects of forced convection and pumping, by increasing the wind speed and making the manikin walk. With this method, the researcher is able to isolate which condition contributes the most to an increase in heat loss. Furthermore, the distribution of

the sweating thermal manikin in multiple zones should allow some evaluation of local effects of ventilation. Depending on vents size and distribution, compared to the manikin zones, differences may be found in heat loss change between the zones, indicating localized ventilation effects.

2.2.1.2. Thermo-regulation modeling.

Time and expenses do not often allow for sweating manikin testing in every environmental condition possible. Instead, thermoregulation or physiological modeling can be used to determine the human response while wearing a particular garment, but in various temperatures and humid environments. There are many different thermoregulation models including those developed by Gordon et al. (1976), Konz et al. (1976), Wissler (1985), Fiala (1999), and Huizenga et al. (1999) (Fiala, Lomas, & Stohrer, 2001). Thermoregulation models can be beneficial for structural turnout ventilation research. Data taken from sweating manikin testing can be input into the RadTherm® software, developed by Thermoanalytics (Calumet, MI, USA) to simulate what would occur in various environmental conditions for each type of protective clothing, or type of ventilation design. This would provide a more comprehensive database on the effects of ventilation in various ensembles and conditions.

2.2.2 Trace Gas Dilution Method and Ventilation Index

A different procedure for estimating the volume of air flowing through the micro-environment of clothing, under various working conditions, is the use of a trace gas dilution method to calculate a ventilation index. The original method, developed by Crockford et al. (1972), requires two techniques; both a measurement of the microenvironment volume and a tracer gas to measure the rate of air exchange (Birnbaum & Crockford, 1978; Crockford,

Crowder, & Prestidge, 1972; Lotens, 1993). Calculations between these two techniques results in the air exchange properties of a garment which can be described in terms of a Ventilation Index (Birnbaum & Crockford, 1978). Calculation of the ventilation index is shown in Equation 2.1:

Equation 2.1 Clothing Ventilation Index

$$Q = R \times V, \text{ where:}$$

Q = ventilation index (liters/minute),

R = air exchange rate (min^{-1}), and

V = micro-environment volume (liters) (Birnbaum & Crockford, 1978).

The Ventilation Index, Q , can be used as a quantitative rating scale, as shown in Figure 2-2 below, which enables comparisons between different garments. The index shows the required liters/minute needed for effective ventilation in various types of clothing with specified activity levels and wind speeds. This would be beneficial research to determine how different ventilation designs perform compared to one another, as well as to compare other types of protective clothing. The Ventilation Index may also be used as an index of volume air exchange.

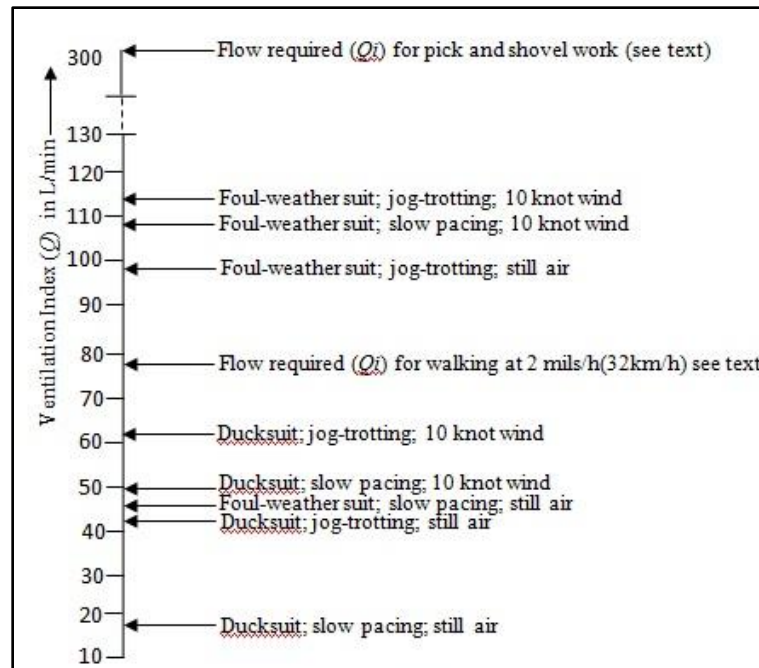


Figure 2-2. Ventilation Index values of selected garments on a linear scale reproduced from (Birnbaum & Crockford, 1978).

Before the introduction of the trace gas dilution method for clothing ventilation measurements, air exchange rates were measured in a similar way for the ventilation of rooms and buildings (Birnbaum & Crockford, 1978; Crockford et al., 1972). Tracer gas methods for clothing involve the use of tubing systems to distribute and sample a tracer gas in the microclimate to determine the ventilation to the environment. These tubing systems are designed to take equivalent samples at different body parts and can be placed on a manikin or human for wear testing. The distribution system for supplying the tracer gas is placed between the undergarments and the clothing system being worn. These tubes are perforated with small holes, proportionate to the surface area of the body which it covers, to distribute

the tracer gas (Birnbaum & Crockford, 1978). The sampling tubing system is placed on the surface of the skin where it continuously samples the microclimate air through a set of equal length tubes, which are only open at their distal ends (Birnbaum & Crockford, 1978). The trace gas method leaves the head, hands and feet free of tubes; areas where clothing is not usually worn (Lotens, 1993).

Reischl and Dukes Dobos adapted Crockford et. al's method in order to consider regional changes in garment designs as separate sections apart from total ventilation (Lumley, Story, & Thomas, 1991). This method allows for local modifications to be made to the garment. They created the second technique for measuring clothing ventilation. This technique is simple and fast, measuring the air exchange rate and air speed (Lumley et al., 1991).

Lotens and Havenith (1988) further developed the Crockford et. al (1972) tracer gas technique using a continuous flow of argon (Ar) instead of Nitrogen (N₂) (G. Havenith, Zhang, Hatcher, & Daanen, 2010; Lotens & G., 1988). Lotens and Havenith developed a steady state method, whereas the Crockford et al. method was an unsteady state method (Ke et al., 2014). A continuous flow of tracer gas is used to look at the steady state dilution of the gas in the microclimate. Because the microenvironment volume does not need to be calculated with this method, and due to its simplicity, it is easier to use in research.

A comparison of the two tracer gas dilution methods was conducted by Havenith et al. (2010) which showed good reproducibility, validity, and usability of both methods (G. Havenith et al., 2010). A major problem with the Crockford et al. method, however, is the technique used to measure the microenvironment volume. This technique is both unreliable

and cumbersome. Further limitations of the Crockford et al. method include the limited time constant of the measurement apparatus which causes an upper limit to the ventilation that can be reliably measured (G. Havenith et al., 2010). The Lotens and Havenith method also has disadvantages. The distribution of the tracer gas over the entire skin surface becomes a problem factor at very high ventilations (above 1000 l/min).

2.2.3 Comparison of Measurement Methods

Compared to the sweating manikin technique alone, the trace gas method for measuring ventilation has some advantages. Its most notable advantage is speed of testing. A measurement can be taken in three to six minutes, instead of one to two hours with a sweating manikin (Crockford et al., 1972; Lotens, 1993). The trace gas method can also be used to measure ventilation at localized body segments, allowing for determination of effective vents placed in specific areas of the garment (G. Havenith et al., 2010; Ke et al., 2014) and it can be used to measure directly on humans wearing the clothing. A sweating manikin, however, will provide thermal and evaporative resistance measurements at various locations of the body, broken down into the zones of the manikin. An advantage of the sweating manikin technique is the calculation of a predicted THL value which relates directly to overall total heat loss and can be compared back to sweating hot plate THL on the fabric level. The sweating manikin also produces both dry and wet heat loss, allowing for the separation of convection and evaporation differences. Both methods have their advantages and disadvantages and both are beneficial. A need exists for future research to compare both methods and validate them against one another.

2.3 Examples of Ventilation Modifications in Protective Clothing

It is important to better understand previous research conducted on ventilation to know what strategies and measurement techniques have proven effective for various types of protective clothing. Previous findings from other areas of protective clothing, such as industrial, military, outdoor and sports apparel, can be used to determine what types of ventilation designs could be incorporated into structural firefighter turnout gear.

2.3.1 Venting in Industrial Protective Clothing

Thermal protection can be important for the clothing of industrial employees such as miners, soldiers, and pilots. These types of thermal protective clothing may also lead to heat stress of the wearer, depending on exact requirements. New materials and design improvements have been introduced in some occupations to help eliminate the accumulation of excess heat and moisture within the microclimate of worker's clothing (Hardcastle, Kenny, Stapleton, & Allen, 2009; Sullivan, Mekjavic, & Kakitsuba, 1987).

To determine how ventilation affects the microclimate humidity during light exercise, the ventilation index was measured in three body locations while wearing five different work shirts (Ueda, Inoue, Matsudaira, Araki, & Havenith, 2006). The study found the chest had the greatest ventilation and the upper arm had the lowest (Ueda et al., 2006). This finding shows that microclimate ventilation differs among the regions of the body due to varying air currents caused by body movements, respiration, fabric drape, and thickness of air layers (Ueda et al., 2006). For these reasons, it is important to measure clothing ventilation at various body regions, not just air permeability of the fabric, as to attain a realistic evaluation of the clothing system (Ueda et al., 2006).

A direct ventilation measurement technique was used to evaluate four helicopter pilot suits for their thermal comfort properties. Four suits were evaluated including two single layer suits, a double layer suit, and a membrane based garment. Results showed that both single layer suits had the fastest rates of air exchange compared to the double layer and membrane based ensembles (Sullivan et al., 1987). The two air permeable suits had an air exchange rate of $0.058 \text{ R, min}^{-1}$ and $0.014 \text{ R, min}^{-1}$, respectively (Sullivan et al., 1987). Results showed the suit with the loosest fit and larger neck, ankle, and wrist openings provided greater area for air to exchange, hence why it performed so well (Sullivan et al., 1987). However, a single layer suit does not provide enough layers and air gaps for adequate thermal protection. The loose fit also impedes the ergonomic function of the garment. Therefore, it is best to increase air exchange by changing fabric permeability and adding garment openings (Sullivan et al., 1987).

2.3.2 Venting in Sports and Outdoor Apparel

Ventilation features are widely used in the sports apparel industry to release body heat and moisture (Xiang Hui Zhang & Li, 2011). The first example is vertical ventilation of the side seams of a t-shirt. In this study, mesh fabrics were studied in sports t-shirts and evaluated on a thermal manikin for their thermal insulation properties. T-shirts that incorporated mesh fabric in various locations, including the chest, back, and vertical side seams, and at different widths, were evaluated (Xiang Hui Zhang & Li, 2011). As the area of the mesh fabric increased, the dry thermal insulation of the t-shirt decreased, showing an increase in heat loss, as would be expected. The t-shirts with mesh designs placed in the

vertical side seams were considered to be the most ideal for releasing body heat (Xiang Hui Zhang & Li, 2011).

Garments in the outdoor clothing arena may be looked at also. Common ventilation designs in this area can be found on outdoor jackets in the form of "pit zips" and eyelet openings in the underarm region. Ruckman et al. (1998) conducted a ventilation study on outdoor jackets using three different designs of venting: "pit zips," "venting pockets," and "venting back," (Ruckman et al., 1998). The "pit zips" were implemented in the underarms as this region demonstrated the greatest perspiration in preliminary research of the study (Ruckman et al., 1998). Figure 2-3 illustrates the design of the "pit zips" in outdoor jackets.

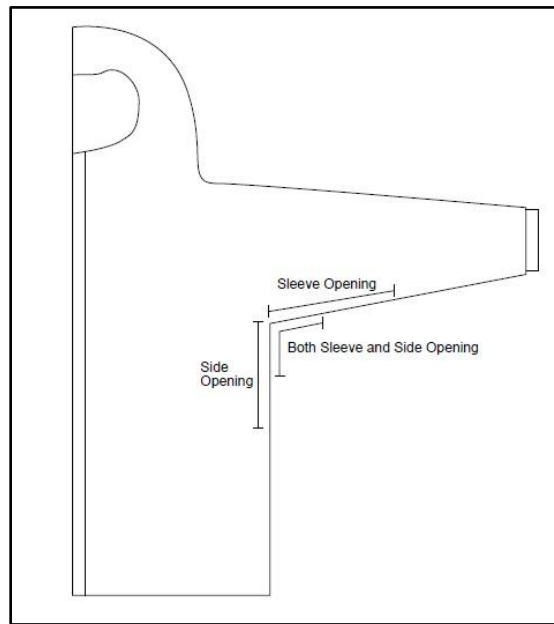


Figure 2-3. Illustration of "pit zips" design in outdoor jackets (Ruckman et al., 1998).

These vents would induce forced convection which would draw in more air through the open vents and allow for greater air and moisture exchange to the outer environment. This design also has the potential to maintain a sufficient amount of protection, even when active, as liquid should not penetrate the area during normal active motions (Ruckman et al., 1998). This study on outdoor jackets found the chest area had the highest skin temperature readings. The authors concluded, therefore, that the chest area should be vented further to increase heat loss in this region (Ruckman et al., 1998).

2.3.3 Venting in Structural Firefighter Turnouts

Research on the ventilation of firefighter turnout gear includes active ventilation strategies, the effect of different moisture barrier materials, and the opening of garment cuffs to reduce heat strain. An original study by Reischl and Stransky evaluated a new structural firefighter prototype which contained a larger neck opening, ventilation spacers, bellows in the sleeves, and vertical ventilation spacers in the pants (Reischl & Stransky, 1980a). The vented prototype had lower heat buildup when compared to the closed clothing system; this difference was attributed to the zippered openings located in the seams of the pants (Reischl & Stransky, 1980a). Design changes were implemented by Reischl et al. (1982) in a second study to create an advanced prototype with increased heat dissipation characteristics. This study included shortening the coat, opening the collar, adding ventilation openings and spacers throughout the coat and pants, and increasing the collar height (Reischl et al., 1982). Conclusions showed improved ventilation in the arm and back regions, but no significant improvement in the chest or leg regions of the prototypes tested (Reischl et al., 1982). The

authors suggested the addition of vertical ventilation openings in the trousers of firefighter turnouts to increase heat loss (Reischl et al., 1982).

A study which evaluated the opening and closing of the sleeve and pant cuffs, opening of the collar, and the replacement of a belt with suspenders, also found positive results for heat loss (Dukes-Dobos et al., 1992). A trace gas dilution technique was used to measure localized ventilation around various regions of the body. This study found the greatest improvement in heat loss was due to ventilation in the chest area when the coat was opened at the collar and in the front (Dukes-Dobos et al., 1992). Opening of the sleeve cuffs did not contribute a great amount to ventilation but the pant cuff opening lead to an increase in ventilation in the leg and crotch areas (Dukes-Dobos et al., 1992). The design of firefighter turnout gear has continuously changed over time, therefore, ventilation research on current designs is necessary.

2.4 Firefighter User Needs

2.4.1 Firefighter Working Conditions

Fire fighting activities account for only 10 to 20% of all duties firefighters perform (Rossi, 2005). Up to 99% of a firefighter's time may be spent performing other firefighter working tasks where the threat of heat and flame is nonexistent (Den Hartog, 2010). These other firefighter working tasks include responding to goodwill calls, emergency medical services, motor vehicle accidents, performing vehicle extrications, and conducting search and rescue operations (FireRescueOne, 2014). Under these conditions, extreme heat and flame exposure does not pose a threat and the heavyweight self-contained breathing apparatus (SCBA) is not worn.

"Overhaul" is a working condition performed by firefighters once a fire is under control. This activity involves opening walls, tearing down ceilings, and extinguishing any remaining hot spots (Sheridan, 2011). In this condition, thermal strain increases greatly as heavy physical activity is performed in an extreme hot and humid environment. Vents with lower exposure level risks may be deployed for improved heat loss in this condition.

The potential for ventilation exists in all firefighter working conditions but is most limited during firefighting operations, within a live fire. Clothing ventilation is most readily applicable during normal working conditions which firefighters perform the majority of their working time. During activities such as vehicular extrication or search and rescue, vents would be beneficial for heat loss and pose no threat for heat and flame exposure.

2.4.2 Firefighter Turnout Ensemble

A traditional, United States, firefighter's turnout ensemble consists of the coat, pants, helmet, hood, SCBA, gloves and boots. Coat and pant garments consist of three component layers: a durable, protective outer shell that serves as the first line of defense; a thin inner layer known as the moisture barrier which prevents water and some chemicals from penetrating through; and the thermal liner which is directly in contact with the firefighter's base layers. The thermal liner provides the majority of thermal protection within the three-layer composite system.

Activities performed by firefighters often involve carrying, pushing, pulling, holding, turning, wielding, throwing, or lifting; all of which can lead to overexertion (Gary M. Kurlick, 2012). The thermal insulation provided by the turnout far exceeds what is necessary for the majority of tasks the firefighter performs that are not fire related, therefore creating a

negative impact on the wearer's comfort between 80-90% of their working time (Rossi, 2005).

For firefighters, the consideration of additional accessories and reinforcement of materials is vital for improving heat loss. The SCBA is required for respiratory protection. It provides critical respiratory support and protection but can also be very cumbersome and adds a substantial amount of weight to the physical work performed by the firefighter (Coca, Kim, Duffy, & Williams, 2011; Dorman & Havenith, 2009; Hooper, Crawford, & Thomas, 2001; Louhevaara, Tuomi, Korhonen, & Jaakkola, 1984). Not only does the SCBA increase the amount of heat produced by the body, it sits in the region of the body where the sweat rate is highest (Smith & Havenith, 2010). The weight of the SCBA has been identified as the factor which negatively affects physiological strain the most, along with its impermeability and fit, by increasing the heart rate and oxygen consumption rate (Coca et al., 2011; Dorman & Havenith, 2009; Hooper et al., 2001).

The SCBA should be worn during firefighting and hazardous materials incidents including overhaul. When firefighters perform other tasks such as vehicle extrication, rescue operations, and even fire investigations, the SCBA is not part of the protective personal equipment (PPE) protocol (“HR/HF Personal Protective Clothing Safety Policy,” 2009). Therefore, vents placed in the back and other regions where the SCBA would eliminate their benefit, is a limitation during firefighting conditions only, which are between 5-20% of a firefighter's working time.

2.4.3 Application of Clothing Ventilation in Structural Firefighter Turnouts

Based upon ventilation designs in other types of protective clothing and performance apparel, implementation into structural firefighter turnouts depends upon the working condition and required level of protection. For example, an open vertical vent or "pit zip" in the underarm region would not be practical during live firefighting conditions. This vent would be potentially beneficial during all other normal working conditions. There are some types of ventilation, however, which may be directly applicable for structural firefighting operations such as rivet vents in outdoor jackets or mesh vents on the inside layers. Future research is needed to evaluate the heat loss potential of these vents in structural firefighter turnouts before being tested on the human wear level.

Other considerations when designing vents into structural firefighter turnouts include environmental conditions and additional equipment worn on top of the suit. Extreme hot or cold environmental conditions could eliminate the benefit of ventilation openings. The ability to open or close vents may also be effected by other components of the turnout ensemble such as the SCBA, additional tools, or gloves. It should be noted the SCBA closing off vents is actually a beneficial design feature that enhances safety during firefighting operating conditions. Ventilation would only be activated when the SCBA was not required for protection. The tactics and training procedures used by fire departments should consider these potential issues with new designs and adjust them accordingly.

2.4.4 Durability and Maintenance Considerations

Currently, there is no research which the author is aware of pertaining to the effect of ventilation designs on the durability, cleaning, and retirement of structural turnout gear as

they have not been widely implemented into such clothing systems. The addition of ventilation creates the need for a re-evaluation of the durability and maintenance of the newly designed garment. National Fire Protection Association (NFPA) 1851, *Standard on Selection, Care, and Maintenance of Structural Fire Fighting Protective Ensembles*, covers the selection, care, cleaning, storage, and retirement of structural turnout gear. Ventilation adds new openings, interfaces, and seams into the turnout creating more opportunities for degradation, abrasion, tears, and potential problems for normal cleaning routines.

Accessories, such as zippers and Velcro closures may need to be added to ensure protection is not compromised during firefighting activities. Such accessories could create issues when cleaning the garment. To ensure durability is maintained with ventilation, additional accessories would need to be included within the NFPA standard for evaluation during both routine and Advanced Visual Inspections (AVI). These inspections include the evaluation of all parts of the full ensemble for rips, tears, cuts, missing hardware, thermal damage, shrinkage, and closure system functionality (NFPA, 2007).

2.4.5 Functionality, Wearability, and Ergonomics

When placing vents within protective clothing, consideration must be given to the overall functional design of the garment, including the end use wearability and range of motion. Functional clothing includes all garment assemblies which are engineered specifically for a pre-defined performance, over and above the garment's normal functions (Gupta, 2011a, 2011b). Structural firefighter gear falls into the protective category of functional clothing where the garment's properties determine life and death for the user (Gupta, 2011b). Essential requirements for the functionality of turnout gear include sufficient

low weight insulation, reduced bulk, improved ergonomic designs, and proper mobility (Gupta, 2011b).

The goal of any new development for the functional design of protective clothing must consider improving the ergonomics and overall comfort of the clothing system, while maintaining the necessary protection (Rossi, 2005). For firefighters, it is imperative their gear be ergonomically designed in order to crawl, crouch, climb, and manipulate their way through various physical obstacles (Gupta, 2011a). The ability to perform these activities should not be reduced by the addition of ventilation into the clothing system. Therefore, some form of ergonomic assessment should be performed to evaluate the new ventilation designs in structural turnout gear.

2.5 Research Strategies for Venting Firefighter Turnouts for Heat Strain Reduction

There are various strategies for designing ventilation systems into protective clothing garments. If the protective clothing involves multiple layers, as is the case for firefighter turnout gear, ventilation of all or only one layer should be explored to determine which strategy is most effective. Placement of the vents within the garment may be dependent upon the amount of heat buildup and sweat which occurs on the specific areas of the body. Further research is necessary to determine this relationship. Extra layers and accessories added to the garment for other purposes, such as radio pockets, suspenders, hook closures, and zippers on firefighter suits specifically, should be considered for their affect on the ventilation system.

2.5.1 Active versus Passive Ventilation

A ventilation design may be active or passive depending upon the type of activity being performed and the necessary protection required. An active vent is one which can be

opened or closed, depending upon the work scenario and its protective requirements. A passive vent is always in place, working to release heat at all times and does not have an open or close feature. In Reischl and Stransky's study (1980) on ventilation of firefighter turnouts, active vents were placed along the inseams of the trousers that could be "opened" or "closed" by using zippers and Velcro closures (Reischl & Stransky, 1980a). These vents would be active during normal working operations, where protection from heat is not necessary, and closed during firefighting activities where direct exposure to flame is a threat. During operations leading up to fighting a fire, such as placing a ladder, unwinding a water hose, and connecting to a fire hydrant, vents can be active, or open. When the firefighter is ready to enter the burning building or fight a fire, the active vents may need to be closed depending upon the type of protection required. Further testing to determine the thermal, liquid, and chemical protection of vented turnouts is needed.

An example of passive vents are grommets, or eyelets, which form small, open circular holes for air to flow through. This type of ventilation feature is often found in sports apparel jackets and pants. These tiny, open holes created by the grommets are most often found in the underarm and groin regions. While these holes may directly expose the base layers of the wearer, they could be implemented into a structural firefighter suit. The placement in the underarms and groin areas should help maintain protection, as those areas are normally covered during standing and walking positions. The ability of this strategy to maintain both thermal and chemical protection would need to be evaluated.

In structural firefighter turnout gear, one such example of a passive vent is a vented moisture barrier (Curtis, 2013). The middle layer of the turnout gear, the moisture barrier,

may be vented around the middle of the torso. A mesh liner is put into place to allow for air and moisture vapor to transfer through. The moisture barrier is often vented in this manner as to maintain liquid protection but increase its ability to allow sweat evaporation to occur (Curtis, 2013). As the patent for a protective garment with vent features by Curtis (2013) shows, these passive vents may be placed in almost any area of the coat or pants including the upper back, sleeves, neck, knees, crotch, and seat of the pants (Curtis, 2013). The Curtis (2013) patent involves placing a pair of vertical vents in the back of the moisture barrier which are formed by gaps, cuts, or openings through the fabric (Curtis, 2013). To provide at least some protection in all positions, the design may include some features, such as loops, which limit the expansion of the vent (Curtis, 2013). These passive vents may be placed in the moisture barrier, outer shell, or both layers.

2.5.2 Full versus Partial Layer Ventilation

As described in the Curtis (2013) patent for protective garment ventilation, structural turnout gear may be vented in one layer or through all three (Curtis, 2013). The moisture barrier layer poses the greatest hindrance for heat loss as Zhiyin et al. (2010) showed in their study on the Water Vapor Transmission Rate (WVTR) of firefighter clothing (Zhiying, Yanmin, & Weiyuan, 2010). The thermal liner, however, has the highest thermal and evaporative resistance of the three layers in the base composite. Ventilation of both the outer shell and moisture barrier may be explored as well. To determine the layer which is most effective for ventilation, research should be conducted in which all three layers are examined individually and together, in various combinations.

It should be noted, the focus of this review article is on traditional, three layer, structural firefighter turnouts. There are other types of suits worn by firefighters for specific work operations or in other geographic regions which involve various differences in fabrication and construction. Both the number of layers and the type of material being vented should be considered.

2.5.3 Garment Placement of Ventilation

Ventilation should be placed in a garment with considerable thought and attention. Areas of the body where sweat occurs more rapidly and at higher volumes should be studied and chosen for ventilation placement. The effect of pumping and forced convection on the placement of vents should not be ignored either. Finally, each garment includes individualized accessories and reinforcements that add layers and different material types to the base composite. These additional layers can impact the effect of venting.

Body sweat mapping studies can be a useful tool for determining where the greatest concentration of perspiration occurs. Smith and Havenith (2010) conducted a body sweat mapping study to investigate regional sweat rates at two exercise intensities (55% and 75% VO_{2max}) in moderately warm conditions (25°C, 50% rh, 2 m s⁻¹ air velocity) on nine male runners (Smith & Havenith, 2010). For ventilation specifically, this study indicates where the greatest amount of sweating occurs. As exercise intensity increased, results from the body sweat mapping study show the sweat rate of all areas of the body, except for the feet and ankles, increase significantly (Smith & Havenith, 2010). The regions of the body with the greatest sweat rates were the upper, middle, and lower back areas, followed by the forehead which had the highest sweat rate for the head region (Smith & Havenith, 2010). Figure 2-4

shows the absolute regional sweat rates from the Smith and Havenith (2010) study at the 75% VO_{2max} exercise rate.

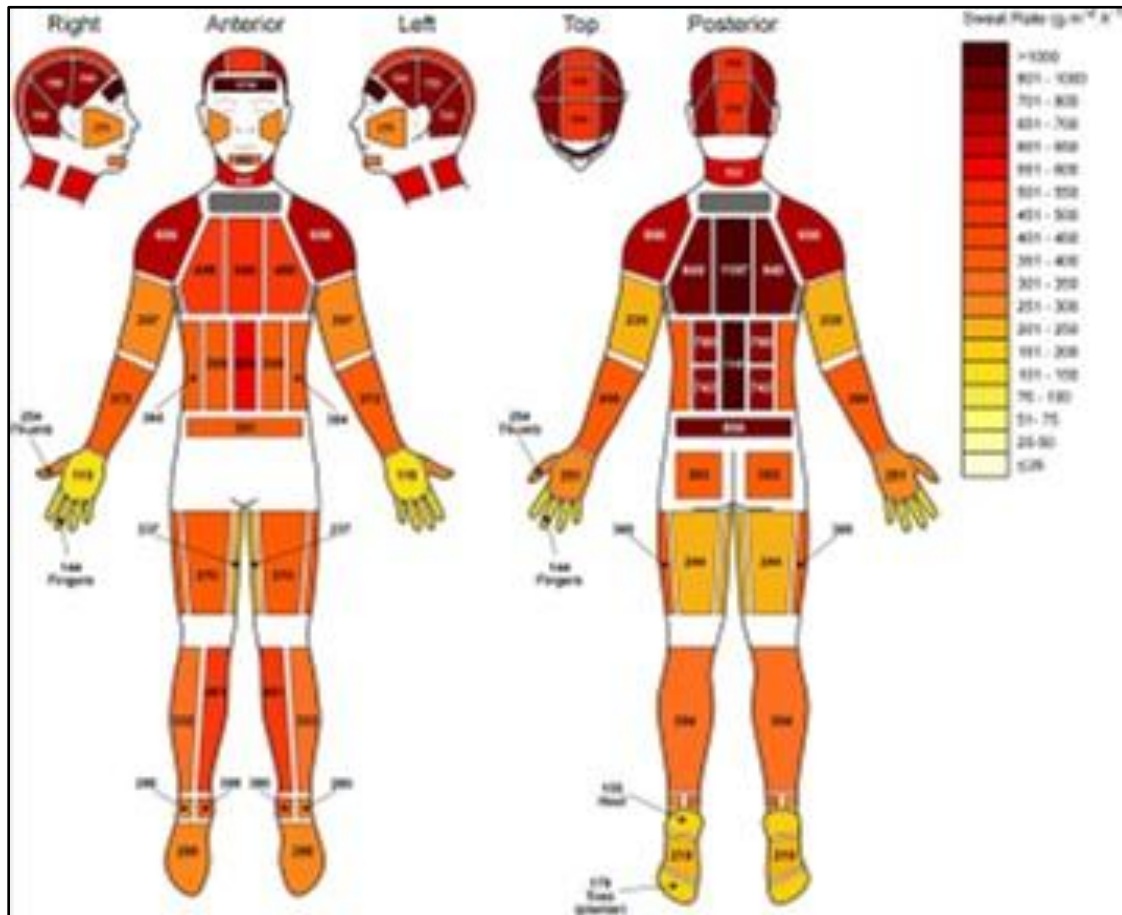


Figure 2-4. Absolute regional median sweat rates of male athletes at 75% VO_{2max} exercise intensity (Smith & Havenith, 2010).

These high sweat regions align with other studies which found the torso and lumbar regions to have the greatest sweat rates of the whole body (George Havenith, Fogarty, Bartlett, Smith, & Ventenat, 2008; Machado-Moreira, Smith, van den Heuvel, Mekjavic, &

Taylor, 2008; Weiner, 1945). Based upon these results, ventilation systems should be placed in these areas to increase the cooling power of the body.

When placing vents within the garment design, their affect on heat loss through pumping, or movement, must be considered. If placed in the wrong area the pumping effect could be hindered or all together removed from the design of the garment. Ventilation should be added to increase the effect of pumping and convective heat loss during movement, such as walking, bending, and crawling. In the firefighter turnout gear ventilation study, conducted by Reischl and Stransky (1980), the lower portion of the back of the coat incorporated a "bellows" design as seen in Figure 2-5 (Reischl & Stransky, 1980a). This bellows design should move counter to body motion and create air movement in the location it was placed (Reischl & Stransky, 1980a). This is an example of pumping effects in a location where sweat rates are at their highest on the body.



Figure 2-5. Bellows ventilation design of structural turnout gear (Reischl & Stransky, 1980a).

Another study which assessed bellows ventilation of clothing, was performed using a human wear trial on one subject to measure skin and microclimate temperature, along with humidity and heat flow (Vokac et al., 1973). The effectiveness of bellows ventilation was demonstrated as the results showed a significant increase in temperature and humidity when motion was suddenly stopped. When walking was resumed, the temperature and humidity dropped and the heat loss increased (Vokac et al., 1973). Literature shows the ability of pumping or bellows ventilation to significantly increase heat loss through sweat evaporation in protective clothing.

2.6 Challenges with Ventilation in Structural Firefighter Turnout Gear

While many of the ventilation strategies described in previous research have proven effective for the relief of heat stress, the most important aspect of firefighter turnout gear, or any protective garment, is its protection. Protective clothing provides a wide range of protection against liquids, steam, heat, flame, chemicals, and toxic gases. A balance must be struck between protection and comfort. Therefore, ventilation designs should not compromise the integrity of a garment by reducing its protection. Three types of protection: liquid, thermal, and gas and vapor will be discussed below along with the corresponding test for evaluation.

2.6.1 Liquid Protection

Firefighters and emergency first responders face the hazard of liquids in the form of chemicals, blood-borne pathogens, and hot water. A recent resurgence in added protection for firefighters against chemical, biological, and radiological hazards occurred following the terrorist attacks of the last decade (Coca et al., 2008). Therefore, venting applications should maintain a sufficient level of liquid protection of the protective clothing. Some ventilation applications directly expose the wearer's skin in the case of open, zipper vents on the outside layers of a structural firefighter suit. These zipper vents would remain open during, "regular work and support operations," but must be closed during firefighting activities (Reischl et al., 1982).

Not only is it important to protect the wearer from toxic chemicals and blood-borne pathogens, but water is a hazard as well. In the act of firefighting, water poses a threat in the form of burns. The majority of burns firefighters suffer from are steam and hot liquid burns

(Kahn, Patel, Lentz, & Bell, 2012). These occur when misuse of protective equipment leads to gaps in the sleeve or face mask, causing burns to the hands and wrist, as well as where the mask meets the face and ears. It is important that as ventilation designs are added, such as open eyelets or open zipper vents, training procedures be put into place to ensure proper protection is maintained during firefighting activities/exercises. These designs should also be evaluated for their protection before being implemented into protective clothing.

Water not only threatens the firefighter in the form of burns, but can also impede the benefit of ventilation by allowing the suit to take on extra weight in the form of liquid. This added weight from water in the suit would lead to a higher metabolic production rate by the body, increased heat storage, and lower heat loss. Therefore, the implementation of ventilation into protective clothing must consider how the specific design will impact liquid protection.

2.6.1.1. Liquid Tight Integrity Test

To demonstrate adequate liquid protection of ventilation designs, a liquid-tight shower test should be performed. NFPA 1992, Standard on Liquid Splash-Protective Ensembles and Clothing for Hazardous Materials Emergencies, specifies testing procedures for liquid-splash protection of protective garments during HAZMAT incidents (DuPont, 2014a; NFPA, 2004). For structural firefighter gear specifically, this standard specifies a "shower" test to demonstrate liquid-tight integrity. Proper liquid protection of protective clothing should prevent the penetration of such liquids as hot water, chemicals, blood, and body fluids from contacting the wearer's skin (J. Stull & Stull, 2012). All clothing by design possesses some form of openings, particularly in the interfaces between layers, in order to

don and doff (J. Stull & Stull, 2012). When adding ventilation designs into protective clothing, it is vital to determine if these openings, whether a mesh fabric, zipper, or eyelet, have an effect on the liquid integrity of the protective garment. If any evidence of liquid on the garment is present at the conclusion of the test, be it visual, tactile, or absorbent toweling, the garment should be considered a failure for liquid-tight integrity (NFPA, 2004).

2.6.2 Thermal Protection

In the case of firefighter turnout gear, thermal protection from heat and flame is the utmost priority for the design and use of the garment. Thermal protection must not be sacrificed for the benefit of heat loss. Ventilation strategies, such as a mesh fabric layer in the moisture barrier, can improve water vapor transport to the outer environment without compromising protection. The firefighter must be protected from both convective heat, which is transferred through air exchange, as well as direct flame during a flashover condition. Open vents, which directly expose the wearer's skin, would pose a danger for both convective heat and flame to burn the wearer if actively "open" during firefighting operations. Therefore, it is important to consider the type of vent and placement on the suit for firefighter protective clothing, not only for liquid protection, but for thermal protection as well.

2.6.2.1 Flash Fire Manikin Evaluation System

To ensure thermal protection of the firefighter turnout has not been compromised by the addition of venting systems, a Thermal Protective Performance (TPP) test on the ensemble level should be performed. A flash fire manikin can be used to evaluate the full ensemble, including the coat and trousers, as well as the boots, gloves, hood, and SCBA

mask (worn without SCBA cylinder). Testing should be completed according to NFPA 1971, *Standard on Protective Ensembles for Structural Fire Fighting and Proximity Fire Fighting* (NFPA, 2013; Prezant, Malley, Barker, Guerth, & Kelly, 2001).

2.6.3 Vapor and Aerosol Protection

Ventilation designs, especially those which are actively open to the environment, cause concern surrounding toxic industrial chemicals and airborne pathogens. Firefighters are routinely exposed to gases and smoke particulates (aerosols) that contaminate the skin if absorbed through the clothing layers. Recent studies have linked the effects of smoke exposure in firefighters to higher risks of cancer and cardiovascular disease (Demers, Heyer, & Rosenstock, 1992; Fabian et al., 2011; Hansen, 1990; LeMasters et al., 2006). Previous studies have found the airborne exposure levels of firefighters, even during overhaul activities, to be greater than the occupational regulatory limits established by the Occupational Safety and Health Administration (OSHA) (Fabian et al., 2011; Glueck et al., 1996; Ide, 2000). The firefighter turnout should not allow hazardous levels of contaminants to be absorbed by the skin, nor should the skin be directly exposed to hazardous levels of toxins during firefighting activities. Therefore, turnouts with ventilation designs should be tested for their chemical protection, taking into account short and long term toxicity effects of the vapors. Those designs which provide benefit towards heat loss and the greatest protection should be implemented into final prototypes.

2.6.3.1. Positive versus Negative Pressure Ventilation

Clothing ensembles are most often negative pressure systems, except those for the highest levels of chemical and biological protection, such as NFPA 1991 impermeable

protective garments, which have additional ventilation from exhaust air or air fans and are designed to be closed, fully encapsulated, positive pressure garments. Structural firefighter turnouts are negative pressure systems in which air from the environment is drawn into the suit naturally, through the collar, cuffs, hems, and pant leg openings, because of the continuous motion and pumping effects. When ventilation openings are implemented, more air can be drawn in from the outer environment and more air from within the clothing system may be transferred outward. On the other hand, when ventilation is added into the suit, whether it be a mesh vent, larger neck opening, or fully vented zipper openings, the pressure difference between the clothing system and the environment decreases. These openings in the fabric and garment design for air exchange decrease the flow resistance between the outside environment and inside of the clothing.

For firefighters, this leads to both thermal and chemical protection concerns, especially as the turnout is often considered as a low class chemical protective suit. In a negative pressure system, the wearer could be more easily exposed to chemicals, flame, liquid, and toxic vapors. Therefore, the specific strategies used for venting a structural firefighter turnout must be carefully evaluated to ensure protection is not compromised. Some research however, shows the addition of air flow into an impermeable system actually increases the protection factor of protective clothing (de Kant, den Hartog, & van Houwelingen, 2011), most likely due to the reduction in negative pressure in the clothing system.

A study on chemical, biological, radiological and nuclear (CBRN) defense protective clothing evaluated the effects of micro perforations in an impermeable liner system (de Kant

et al., 2011). When evaluated through Man-In-Simulant-Testing (MIST), the micro perforations did not have any effect on protection (de Kant et al., 2011). In fact, results showed the air flows underneath the suit were low and the pressure distributions were significant for ventilation (de Kant et al., 2011).

2.6.3.2. MIST Test

The Man-In-Simulant-Test serves to evaluate full protective clothing ensembles for their ability to provide adequate chemical protective performance (Ormond, 2012). MIST testing involves human test subjects wearing full protective ensembles in a specifically designed MIST chamber where they are exposed to a low toxicity simulant for chemical warfare (Ormond, 2012). When considering structural firefighter turnout gear, which is often worn as a low-class chemical protective ensemble, ventilation designs should be evaluated for their impact on chemical protection performance. This testing is ideal for evaluating if the ventilation strategies, zippers, and Velcro added for vent coverings are sufficient for maintaining the garment's original chemical protection, the results should be compared to the protection that currently available garments, with no added ventilation openings, provide.

2.7 Conclusions

Previous research studies demonstrate that ventilation of structural firefighter turnout gear, as well as other types of protective clothing, can be an effective tool for improving human thermal comfort. By reducing the amount of heat buildup within the clothing microclimate, through increasing air exchange and sweat evaporation, heat strain can be reduced. For firefighting in particular, it is essential thermal protection be maintained while balancing the amount of heat buildup within the turnout in order to reduce the amount of heat

strain experienced by the wearer. Various ventilation strategies have been implemented in other areas of protective clothing which achieve this benefit towards heat loss and show promise for its implementation in structural firefighter turnout ensembles.

Future research is necessary to determine which types of ventilation designs are most effective for structural firefighter turnouts, and protective clothing in general. Active and passive ventilation strategies should be evaluated, along with full and partial layer venting. Research is needed to determine how the addition of ventilation impacts thermal, liquid, and chemical protection to the wearer. Various measurement systems including the sweating manikin and trace gas dilution methods should be compared and validated.

Research to determine ways of reducing heat strain in firefighter turnout gear is important for decreasing injuries and fatalities caused directly, or indirectly, by fatigue, decrease in cognitive performance, heat exhaustion, or stroke. The buildup of heat inside clothing can be more detrimental to the health of the wearer than the hazards the protective clothing was originally intended to protect against. Garment ventilation openings are one type of design modification for heat loss that should be explored. This review of ventilation literature and its potential inclusion in structural firefighter gear serves as a prelude to further ventilation research.

*It should be noted that the above chapter has been published in the Textile Research Journal (McQuerry, Den Hartog, Barker, & Ross, 2016).

3 Garment Ventilation Strategies for Improving Heat Loss in Structural Firefighter Clothing Ensembles

3.1 Introduction

Firefighters face multiple thermal hazards, including heat, flame, and high air temperature exposure as well as heat stress within the clothing system due to its protective properties. Structural firefighter turnouts consist of multiple fabric layers for protection against puncture, chemicals, heat and flame, and steam (Reischl & Stransky, 1980a; Xiang Hui Zhang & Li, 2011). The thickness of these multiple layers hinders heat loss as sweat evaporation is reduced due to humidity and lack of air movement within the clothing microclimate (Dukes-Dobos et al., 1992; Reischl & Stransky, 1980b). In order to prevent fatigue, heat exhaustion, heat stress, and stroke a balance must be struck between the necessary level of thermal protection and required heat loss.

To alleviate the buildup of heat within a structural firefighter turnout clothing system, ventilation may be employed. Ventilation is defined as the flow of air over the skin, after passing through fabric layers and/or garment openings, increasing the potential for convective and evaporative heat loss to occur. Garment openings can be implemented into firefighter turnouts in a variety of ways to increase air flow. Previous research, including Reischl and Stransky's studies on the ventilation of structural firefighter turnouts, suggests some ventilation designs are more beneficial than others (Reischl et al., 1982; Reischl & Stransky, 1980a). For example, adding vertical ventilation spacers in the side seams of the trousers (Reischl et al., 1982) and coat (Xiang Hui Zhang & Li, 2011), incorporating "pit zips" in the underarm regions (Ruckman et al., 1998), and incorporating an opening in the

moisture barrier layer (Curtis, 2013). Designs of ventilation openings in fire fighter clothing systems can be modeled after designs found in other types of protective clothing including military, sports, and outdoor apparel (Dukes-Dobos et al., 1992; Hardcastle et al., 2009; Ruckman et al., 1998; Sullivan et al., 1987; Ueda et al., 2006; Xiang Hui Zhang & Li, 2011). It is vital to understand how and why previous ventilation designs have performed in order to implement those most effective in structural firefighter turnout gear.

Turnout gear consists of three components: a durable, protective outer shell which serves as the first line of defense against external threats; a thin, inner layer known as the moisture barrier which prevents water and liquids from penetrating through; and a thermal liner on the inside, closest to the base layers that a firefighter might wear underneath the turnout. The thermal liner and moisture barrier layers together provide over 75% of the thermal protection in the three layer composite (Young, 2010).

The design and placement of ventilation features within the turnout has an impact on the amount of heat loss which can be achieved (Dukes-Dobos et al., 1992; Reischl et al., 1982; Reischl & Stransky, 1980a). There are two different types of clothing ventilation: active and passive. An active vent, in the case of structural turnout gear, can be open during normal working operations, where protection from heat and flame is not necessary, and should be closed during firefighting activities where direct exposure to flame may be a threat. Zipper closures that can be opened or closed based upon the need of the wearer are an example of active vents. Passive ventilation is the second type of venting which may be used. Passive vents are always in place, they are not "opened" or "closed", and they can be located

in any one of the three base composite layers. An example of passive ventilation is a vented moisture barrier (Curtis, 2013).

Based upon previous clothing ventilation research, five individual ventilation turnout designs were created and fabricated into separate standard garments. The purpose of this research was to evaluate the contribution of ventilation to overall heat loss within the firefighter turnout clothing system. The heat loss capability of various ventilation strategies was studied.

3.2 Experimental Methodology

Five different suits, each with their own ventilation design, were tested for thermal resistance, evaporative resistance, and predicted THL using a sweating manikin. A standard control turnout, with no added ventilation design features, was used as a baseline measurement. A thermal sweating manikin was fully dressed in a structural firefighter ensemble including trousers, coat, hood, gloves, boots, self-contained breathing apparatus (SCBA), and SCBA mask. A standard issue cotton t-shirt, athletic shorts, and socks were worn underneath the ensemble as base layers.

Garments evaluated for ventilation were all made from the same outer shell (para- and meta-aramid blend), moisture barrier (PTFE laminate), and thermal liner materials (aramid batting quilted to aramid facecloth). All six garments were made according to the same basic pattern. Figure 3-1 shows six suits with differing ventilation designs that were tested including: 1) a standard control turnout, 2) a passive open vent suit, 3) a passive rivet vent suit, 4) a passive moisture barrier vent suit, 5) an active zipper vent suit, and 6) an active vertical vent suit.

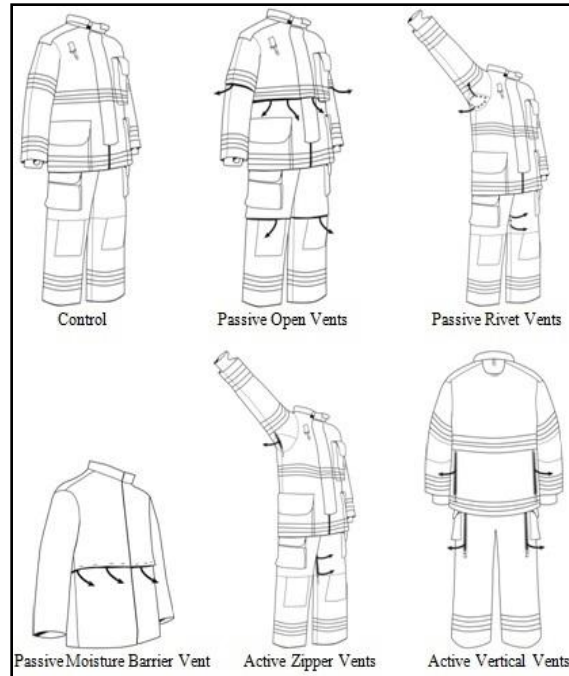


Figure 3-1. Illustration of ventilation designs in structural firefighter turnouts.

The passive open ventilation design had the most exposed areas to allow for ventilation. The suit was vented through all three layers, exposing the wearer's base layers to the external environment. These vents were placed around the mid-torso, upper arm, and mid-thigh regions of the suit. The passive rivet vents, placed in the underarm and groin regions, were tested in the walking conditions only. This design was a minimalist approach to ventilation. Twelve rivets were placed in each underarm region and six were placed in the groin region, through all three layers of the composite. Compared to the other four ventilation designs, the rivet vents were smaller in surface area and allowed for the least amount of ventilation to potentially occur. Therefore, the greatest possibility for heat loss would be when both pumping and forced convection are present in the dynamic test condition. The

passive moisture barrier vent was placed in the middle layer of the coat composite only. This ventilation design created a horizontal opening in the torso of the coat's moisture barrier layer for air to flow through more freely.

Two active ventilation designs were also fabricated. The active zipper vents were placed in the underarm and groin region of the trousers. A 15 centimeter cut was made through all three layers exposing the wearer's base layers in these areas. One opening was made in each underarm and on each side of the inner pant seam in the groin area. A second ventilation design, the active vertical vents, was fabricated in a similar manner but placed in different regions of the suit. Long, vertical openings were cut in the vertical side seams of the coat, from the bottom of the middle torso trim to the top of the lower hem trim. The same was done to the trousers, openings were cut starting underneath the waistline to below the pockets, on the side seams.

Vents were placed in both the coat and trousers of the turnout in all designs except for the passive moisture barrier vent which was placed only in the moisture barrier layer of the turnout coat. Vents were placed through all three layers of the turnout composite except for the passive moisture barrier vent. These six suits were tested on a sweating manikin for both thermal and evaporative resistance. Calculations were performed to determine the predicted THL of each suit.

Based upon the performance of each ventilated turnout, those designs which showed a statistically significant improvement in THL, compared to the Control, were further tested in a vehicle extrication scenario. The manikin was dressed in the turnout ensemble along with gloves, boots and a helmet. The thermal hood, SCBA, and SCBA mask were not worn.

The purpose of this additional research was to determine the heat loss performance of the vented openings in a more realistic fire fighting scenario. Due to the increased risk of active or open vents in a structural fire, it is more probable that vents would be activated in a vehicle extrication scenario in which heat and flame do not pose a risk.

3.2.1 Procedures

Testing to evaluate each ventilated turnout was completed using a sweating thermal manikin. The 34 zone model includes separately controlled heated sections with built-in pores for sweating and a fluid pre-heater inside the manikin to ensure the "sweat" coming through the pores is maintained at the proper temperature (Measurement Technology Northwest, 2007). The manikin is connected to a computer software program which monitors the heaters, fluid temperature, manikin temperature, and flow set points for each zone section. The standard control and ventilated turnouts were evaluated in the following four conditions shown in Table 3-1.

Table 3-1. Sweating manikin testing conditions.

Condition	Air Speed	Movement
Standing with still air	0.4 m/sec	Standing
Walking with still air	0.4 m/sec	Walking
Standing with wind	2 m/sec	Standing
Walking with wind	2 m/sec	Walking

Natural convection (standing with still air), pumping (walking with still air), and forced convection (standing with wind) were evaluated for each vented suit in both 'dry'

(convective heat loss) and ‘wet’ (evaporative heat loss) tests. A dynamic condition (walking with wind) was added to determine the maximum amount of ventilation achieved by the garment openings when both air and body movement occur. The passive rivet vent suit was a minimalist approach towards ventilation, with little area of the garment actually opened for ventilation to the outer environment. Therefore, this turnout design was evaluated in the two walking conditions only (walking with still air and walking with wind) to determine if any ventilation effect occurred. For each suit, six replications (three dry manikin tests and three wet manikin tests) were performed, in each of the four conditions, and an average THL was calculated.

For the extrication scenario testing, the two ventilated turnouts with the highest THL performance were selected for further sweating manikin testing. These suits, along with the Control, were tested in the static (standing with still air) and dynamic (walking with wind) test conditions only.

3.2.2 Total Heat Loss (THL) on a Sweating Manikin

Evaluating THL on the manikin level allows for the entire ensemble to be assessed, including pockets, accessories, boots, gloves, hood, and helmet. This method takes into account the amount of body surface area covered by different materials and various numbers of layers, the fit of the garment, and the increased surface area for heat loss (Ross et al., 2012; Walker, 2013). The THL method was originally developed for use with a sweating guarded hot plate on the fabric level only, with calculations assuming measurements are made in identical, non-isothermal conditions (25°C/65% rh). For manikin testing however, per ASTM F1291-10 *Standard Test Method for Measuring the Thermal Insulation of*

Clothing Using a Heated Manikin and ASTM F2370-10 Standard Test Method for Measuring the Evaporative Resistance of Clothing Using a Sweating Manikin standards, dissimilar testing environments are required.

Manikin measurements were conducted in a 23°C/50% relative humidity environment for thermal resistance and a 35°C/40% rh environment for evaporative resistance (Ross et al., 2012). Because manikin THL calculations are based upon measurements taken in two different environments, the heat loss values are predictive rather than actual measurements (Ross et al., 2012). The assumptions of the manikin THL calculation are that condensation and absorption have a negligible effect on heat transfer and the thermal and evaporative resistance of the tested fabric is independent of the ambient temperature and humidity (Ross et al., 2012). With these assumptions in mind, the predicted THL (Q_t) for a 25°C and 65% relative humidity environment can be calculated based on the thermal and evaporative resistance (R_t and R_{et}) measurements from the sweating manikin according to Equation 3.1 (Ross et al., 2012).

Equation 3.1 Predicted Manikin THL

$$Q_{t(\text{predicted,T,RH})} = \frac{T_s - T_a}{I_{tot}} + \frac{P_s - P_a}{I_{tot,e}}, \text{ where: } \quad (3.1)$$

$Q_{t(\text{predicted,T,RH})}$ = predicted manikin THL for specified environmental conditions (W/m²),

T = specified temperature condition (°C),

RH = specified relative humidity (%),

T_s = specified temperature at the manikin surface (°C),

T_a = specified temperature of the local environment (°C),

P_s = calculated water vapor pressure at the surface of the manikin (kPa),

P_a = calculated water vapor pressure in the specified local environment (kPa),

I_{tot} = total thermal resistance of the clothing ensemble and surface air layer
($^{\circ}\text{C}\cdot\text{m}^2/\text{W}$),

$I_{tot,e}$ = total evaporative resistance of the test ensemble and surface air layer
($\text{kPa}\cdot\text{m}^2/\text{W}$) (McCullough, Jones, & Huck, 1985; Ross et al., 2012).

3.2.3 Statistical Analysis

To determine the statistical significance of the measured differences in predicted manikin THL, compared to the baseline control, two-sample t-tests, assuming equal variances, were performed. All data was tested for normalcy and normal distributions were confirmed through a probability plot and the Anderson-Darling test statistic. A one-way ANOVA was conducted with each data set (for each condition) to determine if significant differences were present. If differences were identified between the results, t-tests were carried out to determine the significant differences between suit comparisons. All sets of data in this study showed significant differences, therefore, t-tests were conducted comparing each ventilated suit to the control, and all other suits, for each of the four test conditions. A p-value less than 0.05 indicates a significant difference in THL between the control suit and the ventilated suit.

3.3 Results

3.3.1 Structural Ensemble Sweating Manikin THL

The predicted manikin THL results of each suit, in a 25°C, 65% relative humidity environment, were compared to the standard turnout control. Three of the five suits, including the passive open vent, active zipper vent, and active vertical vent, showed statistically significant improvements in heat loss while two of the passive systems did not. A graphical illustration of all six suits, in all four test conditions, is shown in Figure 3-2. Error bars represent standard deviation of the data and the statistical difference between suits in each condition. There are no results for the passive rivet vent suit in the standing conditions because it was a minimalist approach to venting and evaluated in the walking conditions only.

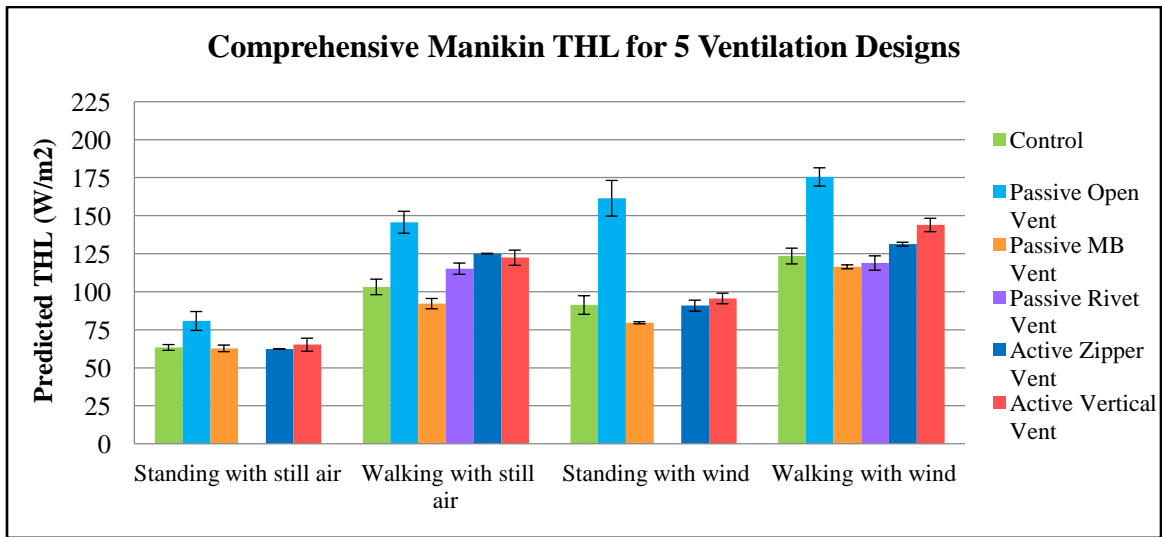


Figure 3-2. Overall predicted manikin THL results of all ventilated suits in the four test conditions, compared to the baseline control.

To further understand the differences in heat loss between the ventilated designs and the control suit, heat loss measurements were related to the surface area of the ventilation openings. Table 3-2 provides specific heat loss data for each vented suit in the dynamic test condition (walking with wind), as well as, the calculated surface area for the vent openings in each suit. The percent increase in THL for each suit between the static condition (standing no wind) and the dynamic condition is included as well.

Table 3-2. Surface area of vents and percent increase in THL.

Ventilated Suit	Surface Area of Vents	Predicted Manikin Heat Loss (W/m²)	% Increase from Static to Dynamic
Control	---	123.5	---
Passive Open Vents	2501.65 cm ²	175.5	117.2%
Passive Moisture Barrier Vent	332 cm ²	116.4	85.8%
Passive Rivet Vents	23.56 cm ²	118.9	3.2%*
Active Zipper Vents	161.29 cm ²	131.3	110.4%
Active Vertical Vents	354 cm ²	143.9	120.7%

*The passive rivet vents were tested only in the walking no wind and walking with wind conditions, therefore, the percent increase in THL is between these two conditions.

The passive open vent design had the highest THL and the largest ventilated surface area of the five suits, leading to a 117.2% increase in heat loss when both wind and motion were added to the test condition. The passive rivet vents had the lowest ventilated surface area and a THL value lower than the control suit, due to test variability. Both the passive moisture barrier vent and the active vertical vents had similar ventilated surface areas

between 330 and 360 cm², however, the design and placement of the vents within the turnout influenced the heat loss performance more so than surface area.

3.3.1.1. Passive Open Ventilation

This suit showed statistically significant ($p < 0.05$) higher heat loss, compared to the control, in all four test conditions. The improvement in heat loss, compared to the control, was greatest in the standing with wind condition, where a 77% increase in heat loss was measured. A 42% increase in THL was determined in the walking with wind condition. For this specific ventilation design, forced convection through wind was the greatest contributor to increased heat loss.

3.3.1.2. Passive Moisture Barrier Ventilation

This suit was found to have the lowest increase in heat loss, compared to the control garment, of the five designs tested. In the walking with wind condition, the passive moisture barrier vent had a decrease in THL of 5.75%, compared to the control in the same condition. In the natural convection condition, there was only a 0.95% decrease in THL, compared to the control, while there was over a 10% decrease ($p < 0.05$) in THL in the wind and pumping isolation conditions.

3.3.1.3. Passive Rivet Ventilation

The passive rivet vent had an 11.6% (115 W/m²) increase and a 3.7% decrease (119 W/m²) in THL in the walking with still air and walking with wind conditions, respectively. The increase in THL in the pumping isolation condition was found to be statistically significant ($p < 0.05$). While THL in the walking with wind condition was slightly less than the control, it was not a significant decrease. From these initial results, it can be concluded

that rivet ventilation in structural turnout garments is not sufficient for increasing THL or reducing heat stress.

3.3.1.4. Active Zipper Ventilation

The active zipper vent suit resulted in a statistically significant ($p < 0.05$) improvement in THL, compared to the control, in both walking conditions. The greatest increase in heat loss, compared to the control, was in the walking with still air condition. Pumping effects in this condition contributed to a 21% increase in heat loss. There was a 6.3% increase in heat loss in the walking with wind condition compared to the control.

3.3.1.5. Active Vertical Ventilation

Vertical ventilation resulted in statistically significant ($p < 0.05$) improvements in heat loss, compared to the control, in the walking conditions only. Regardless of whether wind was present, results showed a significant increase in heat loss in both walking conditions. Pumping, due to walking, was found to be the biggest contributor towards heat loss for the vertical vents. In the walking with still air condition, the addition of pumping, compared to the control, created a 19% increase in THL. For the walking with wind condition, a 17% increase in THL was evidenced.

3.3.2 Garment Ventilation Placement: Coat versus Trousers

To better determine where to place ventilation openings within the garment, an analysis between the turnout coat and turnout pant THL values was conducted. The THL value for each suit was divided by the upper and lower body manikin zones to calculate an overall coat and trouser THL for each ventilation design tested. When comparing the THL values from the upper and lower body zones (Figures 3-3 and 3-4 below) on the same scale,

from zero to 250 W/m², there is much greater heat loss occurring in the turnout trousers than in the turnout coat. For example, the passive open vent in the dynamic (walking with wind) condition had a THL of 220 W/m² in the trousers compared to 136 W/m² in the coat. These differences are especially pronounced for the passive open vent and both active vents in the test conditions where forced convection, from either wind or body movement, is present.

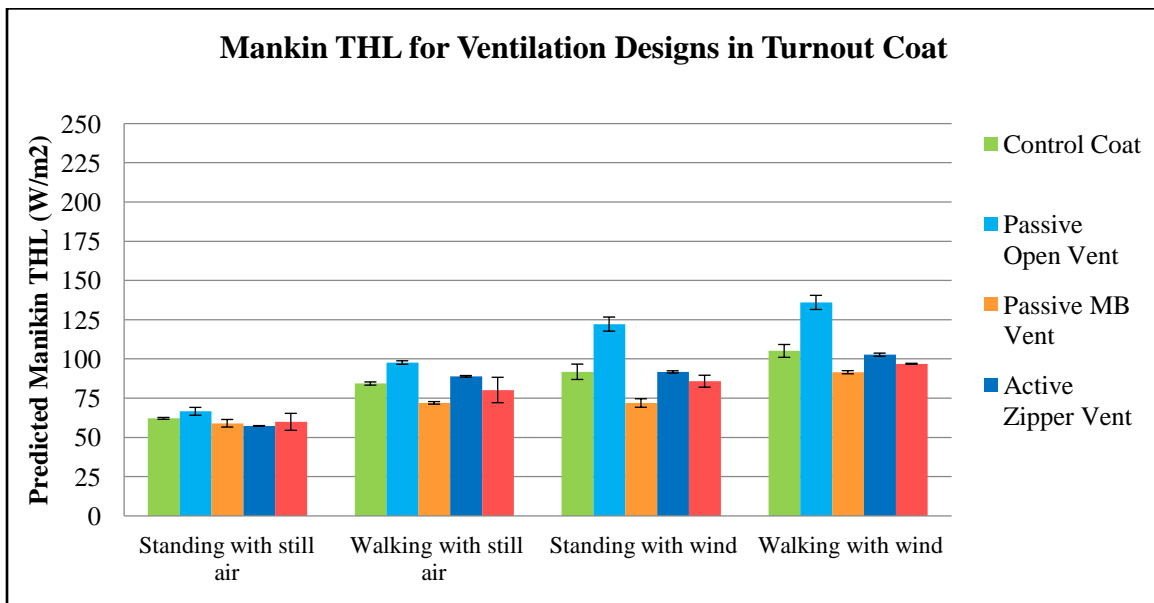


Figure 3-3. Predicted manikin THL results for ventilated designs in the turnout coat area only.

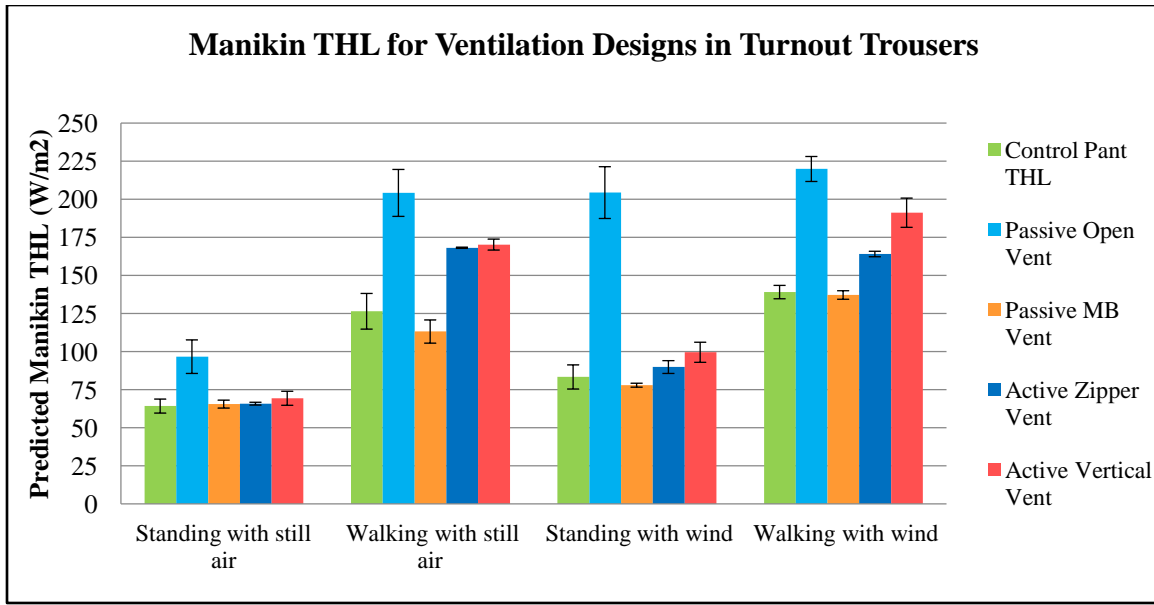


Figure 3-4. Predicted manikin THL results for ventilated designs in the turnout trouser area only.

3.3.3 Extrication Ensemble Sweating Manikin THL

One active and one passive ventilation design was chosen from the five previously evaluated designs. Both the passive open vent and the active vertical vent designs showed a significant improvement in heat loss compared to the Control. These two ventilated turnouts, along with the Control, were tested in static (standing with still air) and dynamic (walking with wind) conditions wearing an extrication ensemble. The extrication ensemble consisted of the coat, trousers, boots, gloves, and helmet. The thermal hood, SCBA, and SCBA mask were not worn. The same base ensemble of athletic shorts, cotton t-shirt, and socks was worn underneath each suit. Figures 3-5 and 3-6 below demonstrate the heat loss values of the

passive open vent and active vertical vent designs, compared to the control, when wearing an extrication ensemble, in the static and dynamic test conditions, respectively.

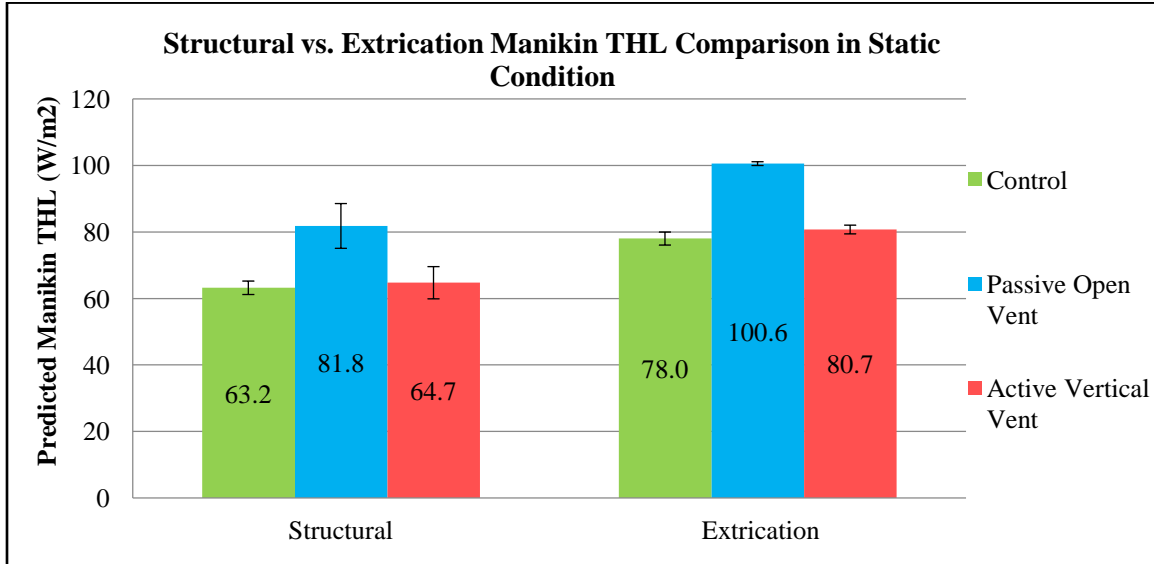


Figure 3-5. Predicted manikin THL results for ventilated designs in a structural versus extrication scenario, in the static test condition.

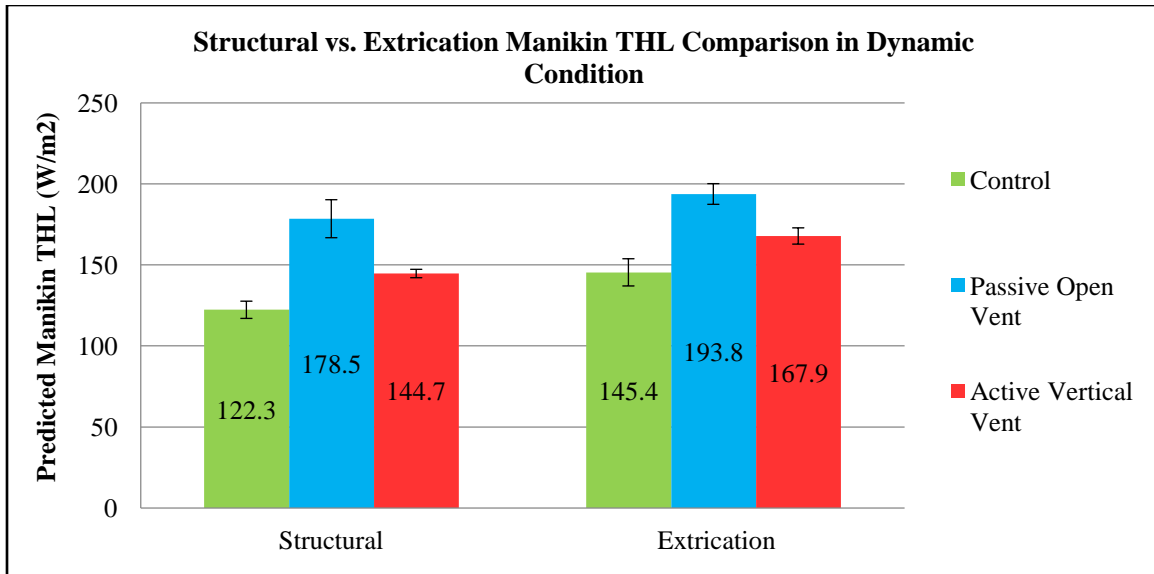


Figure 3-6. Predicted manikin THL results for ventilated designs in a structural versus extrication scenario, in the dynamic test condition.

All suits tested had significantly higher THL when wearing a vehicle extrication ensemble, including the control, except for the passive open vent suit in the dynamic test condition. While the THL of the passive open vent increased when removing the SCBA in an extrication ensemble (15.3 W/m²) it was not determined to be statistically significant ($p < 0.05$) when walking and wind was present. For the active vertical vent suit, however, the improvement in THL when removing the SCBA was statistically significant ($p < 0.05$) in both test conditions. Even the control had a significantly greater THL ($p < 0.05$) when removing the SCBA, mask, and thermal hood, regardless of test condition. These results demonstrate the detrimental effect of the SCBA on clothing ventilation and heat loss.

3.4 Discussion and Conclusion

3.4.1 Structural Ensemble Sweating Manikin THL

Results show three of the five ventilation designs tested were effective for improving heat loss in current structural firefighter turnouts compared to the control garment. Of the three passive vent designs tested, only one demonstrated a statistically significant improvement in manikin THL. The passive open vent had the greatest improvement in heat loss, of all designs tested, in all four test conditions.

The passive moisture barrier vent and passive rivet vents were not successful in increasing heat loss above what is already provided in current turnout designs without ventilation. The lack of improvement with these designs is most likely due to their placement and size. The passive rivet vents were only 1 cm wide, with a surface area of 23.6 cm² for a total of 30 rivets placed in the underarms and groin regions of the suit. The small surface area of the rivet vents, compared to the other designs (354 cm² for the active vertical vents and 2501 cm² for the passive open vents) most likely contributed to the limited effect on heat loss. The active zipper vents were placed in the same areas (underarms and groin) of the garment as the passive rivet vents, however, the surface area of these zipper vents was 161.3 cm² compared to just 23.6 cm² for the rivet vents. This increase in ventilated surface area in the same isolated segments led to a significant improvement in heat loss for the overall garment.

The passive moisture barrier vent was placed in the middle of the three layer composite, around the torso only. This passive vent consisted of a 2.5 cm wide gap, around the torso circumference of the coat (133 cm), resulting in a ventilated surface area of

approximately 332cm². The surface area is similar to the active vertical vents (354 cm²) but did not produce a significant increase in heat loss, most likely due to the placement of the moisture barrier vent. While air flow may have increased through the moisture barrier vent, by sandwiching it between the thermal liner and outer shell, air was not able to escape to the external environment. Ventilation of only a single layer minimized the potential impact of this vent design. Instead, the vent should be extended through all three layers of the base composite in order to achieve an improvement in heat loss. The resting position of the SCBA further decreased the ability of this vent to function properly. Future research should be completed in the trousers with multiple vents placed horizontally along the length of the moisture barrier pant leg. This would determine the ability of this type of passive vent to increase heat loss.

Both active vent designs showed statistically significant increases in THL in the walking conditions. These vents require pumping action, through manikin movement, to effectively release heat from the body. For the active zipper vent, in the standing conditions, the lack of heat loss improvement is most likely due to vent placement. The underarm vents are essentially closed off in the standing manikin position with the arms hanging down on each side. The same is true of the vents in the groin region. For both active vents, their success can be attributed to pumping, in which, air is pulled into and pushed out of the garment openings as the arms and legs move back and forth.

3.4.2 Garment Ventilation Placement: Coat versus Trousers

From the results shown in Figures 3-3 and 3-4, it can be determined that ventilation has a larger impact when placed in the lower body region of a protective clothing garment.

Because the legs are often moving, creating a pumping motion which forces air inward and back out of the clothing system, convective air flow is greater in the trousers than in the coat. While the arms function in a similar way, the SCBA rests in the back region of the coat and prevents air movement throughout the clothing microclimate. The shoulder and waist straps create separate pockets of air which prevents air flow underneath the clothing in certain areas.

3.4.3 Effect of SCBA Removal on Ventilation in an Extrication Ensemble

The results of clothing ventilation testing in an extrication ensemble (no SCBA, mask, or hood) showed statistically significant improvements in THL, regardless of the test condition. These increases in heat loss may be attributed to the removal of the SCBA which compresses the back of the coat and creates pockets of air that do not allow movement throughout the clothing microclimate. By removing the SCBA, and its straps along the shoulders and waist, the clothing microclimate is no longer restricted and air may flow more freely throughout the garment and ventilation openings.

Overall, it can be concluded that the two active vent concepts and the passive open vent design should be implemented into structural firefighter prototypes for further evaluation on the human wear level. Human thermal physiological modeling should be conducted as a next step to predict the influence of these vented suits on physiological responses such as core temperature, skin temperature, and sweat rates. Future testing and human wear trial evaluations should be conducted in a vehicle extrication scenario or firefighting activity scenario where the SCBA is not required. Such activities can constitute up to 99% of a firefighter's time (Den Hartog, 2010). It is also more probable that ventilation

openings would be implemented in such a scenario as extrication or urban search and rescue, where the risk of heat and flame is not present.

*It should be noted that portions of the above chapter have been published in the AATCC Journal of Research (McQuerry, DenHartog, & Barker, 2016b).

4 Alternative Methodologies for Determining the Impact of Clothing Ventilation on Improved Physiological Comfort

4.1 Introduction

In the previous chapter, the results of five ventilated turnout designs are presented and discussed in terms of THL. While sweating manikin technology provides the researcher with an objective measurement of heat loss, in terms of W/m^2 , other methodologies may be used to determine the impact of clothing ventilation on heat loss and physiological comfort. In this chapter, three additional tools and methodologies are described and implemented for further analysis of the aforementioned data set. These tools include visual ratio calculations for each isolated zone of the sweating manikin, virtual modeling predictions of human physiological responses, and estimated ventilation calculations according to the traditional trace gas dilution method. The thermal insulation, evaporative resistance, and predicted manikin THL values from Chapter 3 were used to further analyze the impact of individual ventilation designs on heat loss.

4.2 THL Ratios of Isolated Manikin Zones

4.2.1 Experimental Methodology for THL Ratios

A visual representation of improvements in heat loss was further developed for each of the 34 isolated manikin zones. The output of this analysis is a visual depiction of heat loss for each manikin zone along with a ratio value. Any number above 1 indicates an improvement in heat loss, compared to the control; any number below 1 indicates less heat loss than the control in that area. If the ratio is equal to 1, the heat loss in that zone is

identical to the control. This tool was originally developed within this study for further visual analysis of the THL data in specific areas where ventilation openings were placed.

Using the average manikin THL values for each ventilated turnout when tested in a structural firefighting ensemble, compared to the control, the following calculation was completed, according to Equation 4.1 for each of the 34 manikin zones:

Equation 4.1 Isolated Manikin Zone THL Ratio

$$THL\ Ratio = M2 \div M1, \text{ where: } \quad (4.1)$$

$M2$ = THL of vented turnout zone, and

$M1$ = THL of control turnout zone.

The individual manikin zone ratios were then plotted into a visual depiction of the front and back of the manikin. These calculations and visual representatives were completed for each of the five ventilated turnout designs, in all four test conditions. The resulting data shows zones with the greatest increase in heat loss and provides a percentage of heat loss improvement compared to the control. Significant differences between zones were not analyzed in the scope of this study. However, this method of visualizing manikin THL data provides researchers with a more direct interpretation of localized differences due to clothing ventilation.

4.2.2 Results and Discussion of Manikin THL Ratios

The individual THL ratios for each of the ventilated turnout designs, in the dynamic test condition, are shown in Figures 4-1 through 4-5 below. It should be noted that while overall THL values are highest in the dynamic test condition, differences in heat loss between the suits and the control may be greater in other test conditions. For the purpose of

this analysis, THL ratios in the dynamic condition only will be discussed. The THL ratios in the static, pumping, and wind isolation conditions can be found in Appendix A.

The ratios are on both a number scale, between 0 and 3, and a color scale, from red to blue. The "red" zones indicate lower levels of heat being lost, whereas the "blue" zones, represent higher levels of heat being lost. The greater the number is above "1", the greater the heat loss above the control. For example, if a manikin zone has a ratio of 2.9, the heat loss in that area is 290% greater than the control. However, if a manikin zone ratio is less than "1", with a ratio of 0.6, that indicates the heat loss in this area is six times lower than the control. Ratios between 0.8 to 1.2 are most likely due to test variation, not a significant representative change in heat loss due to clothing ventilation. An increase above 30-40% in heat loss, however, is most likely significant on a physiological level. Further physiological heat strain testing must be conducted in order to determine this significance.

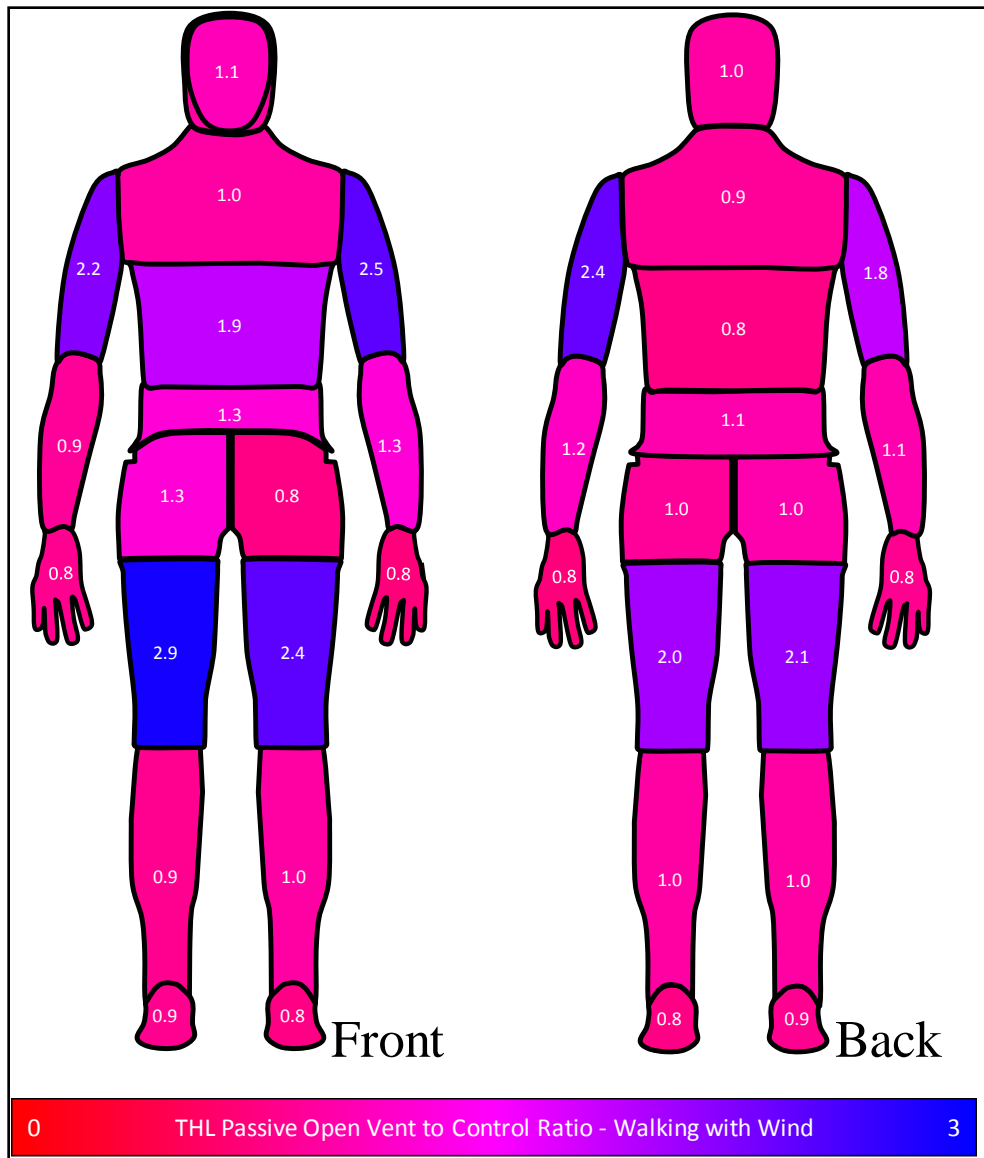


Figure 4-1. Passive open vent THL ratio in dynamic test condition.

In the dynamic condition, an overall increase in THL of 42% was measured for the POV concept. Figure 4-1 illustrates the areas where the majority of the increases in heat loss occurred: the mid-thigh, middle front torso, and upper arm regions. These regions correspond

to the specific placement of ventilation openings in the garment. No improvement in heat loss was measured in the back of the torso, even though venting was placed there. This lack of improvement is most likely due to the resting placement of the SCBA on the manikin's back during testing.

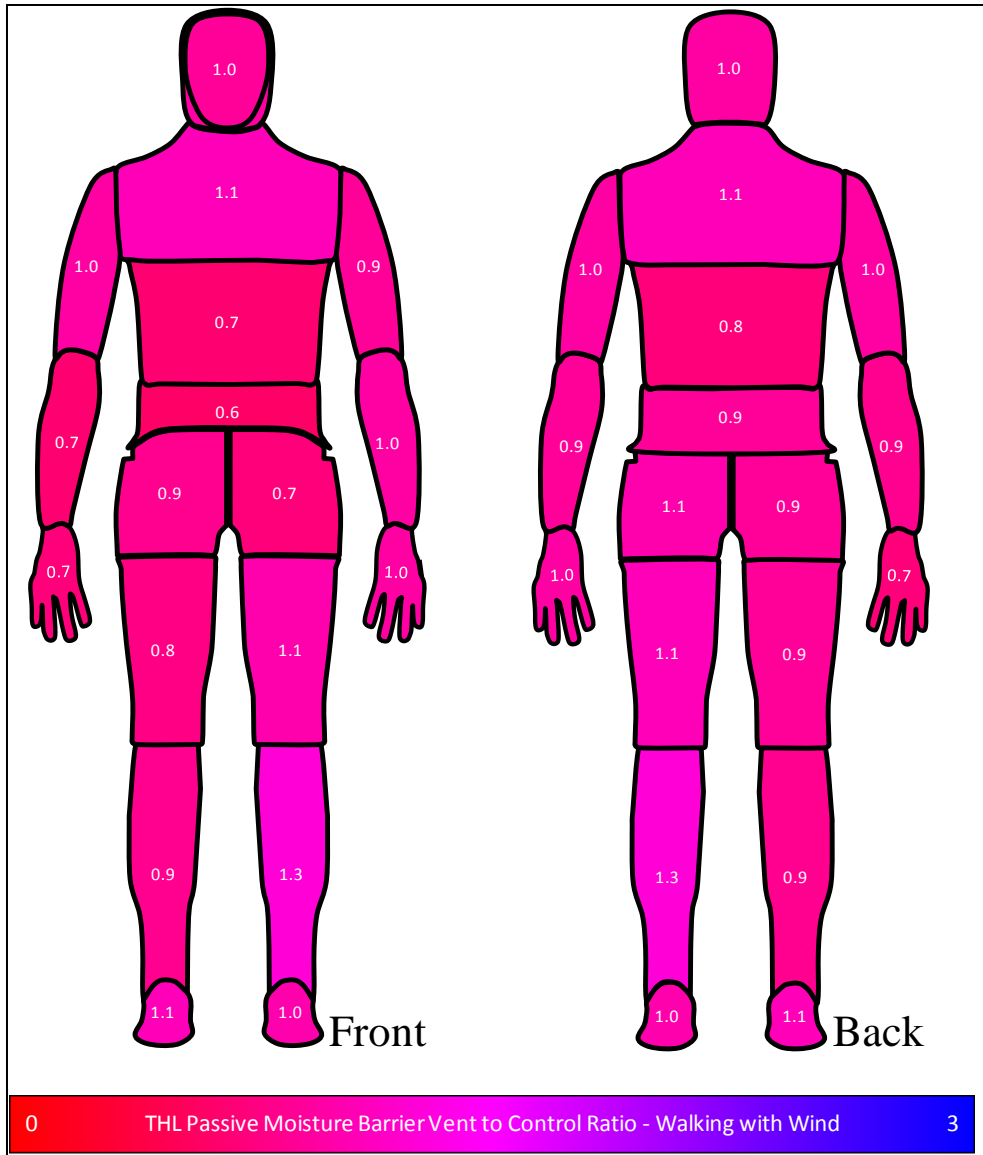


Figure 4-2. Passive moisture barrier vent THL ratio in dynamic test condition.

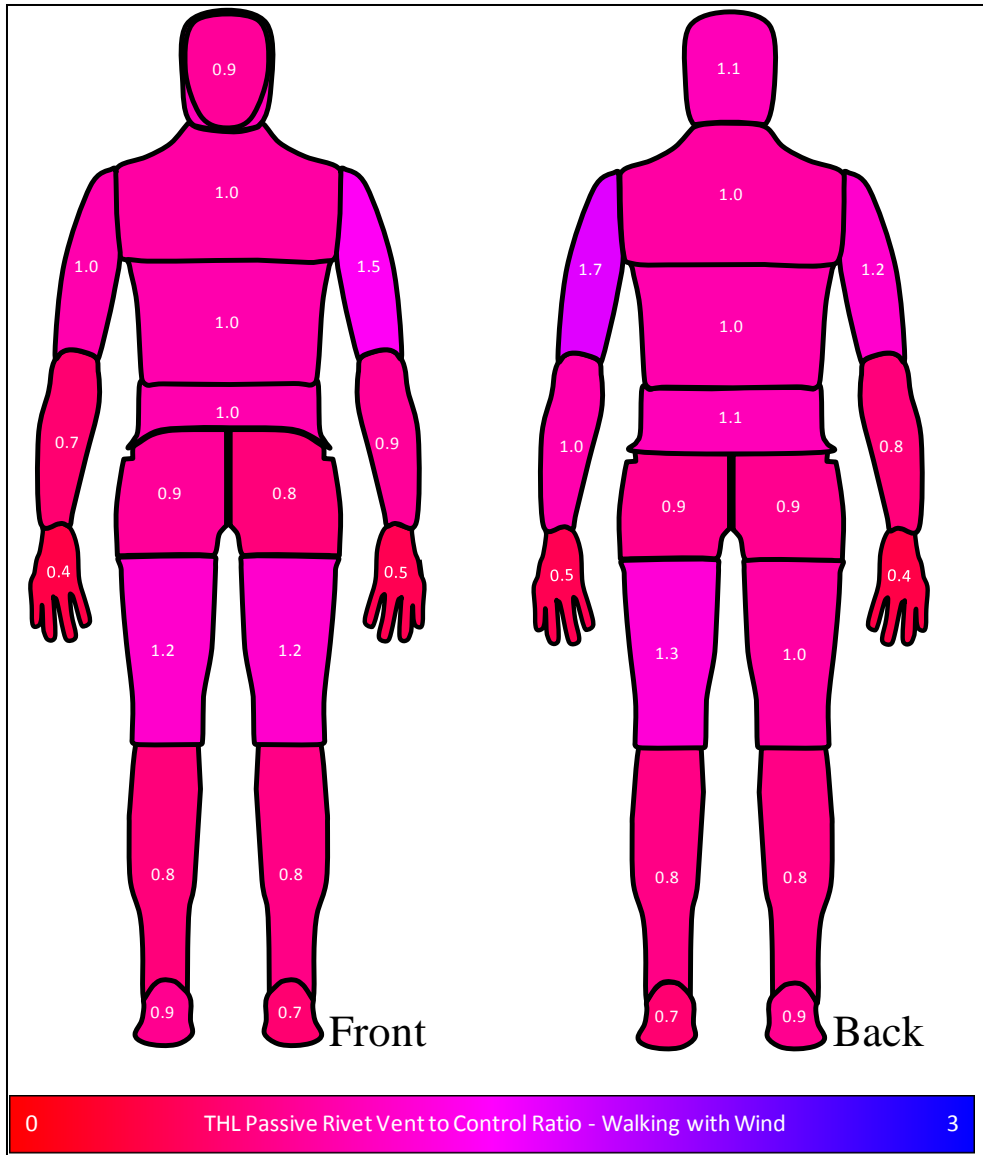


Figure 4-3. Passive rivet vent THL ratio in dynamic test condition.

In the two passive ventilation systems above, the moisture barrier and rivet vents both showed little to no improvement in overall THL. This is further confirmed by the ratio analysis which shows values between 0.7 and 1.3 for the moisture barrier vent. These

differences are most likely due to slight test variation and correspond with the overall THL results from Chapter 3, that no improvement in heat loss is detected with this design.

Figure 4-3 shows the THL ratios for each zone of the passive rivet vent suit. We do see slight improvements in the upper arm (1.2-1.7) and upper leg regions (1.2-1.3) where the rivets were placed. However, these differences are negligible and could also simply be due to test variations. Either way, they are not significant for improving heat loss.

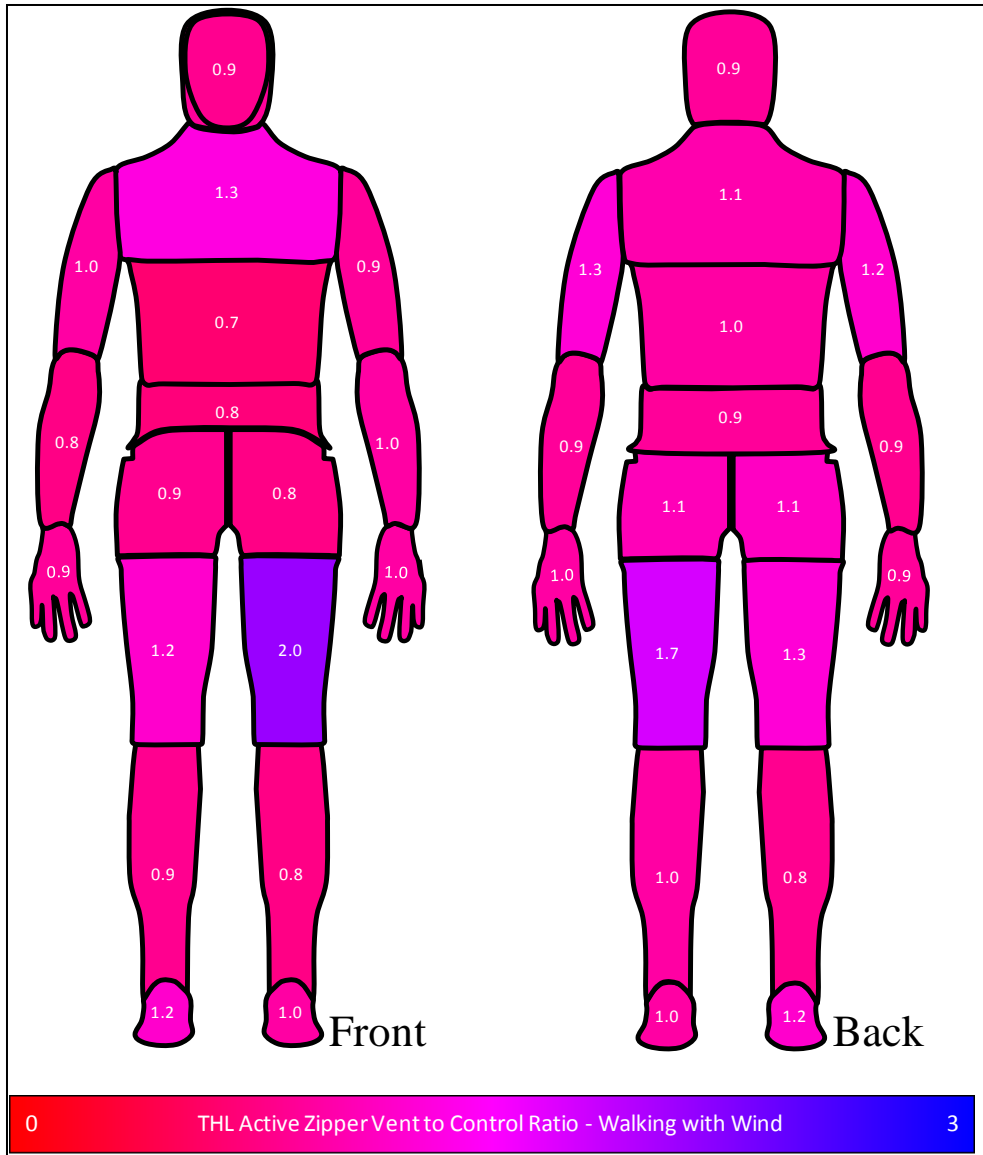


Figure 4-4. Active zipper vent THL ratio in dynamic test condition.

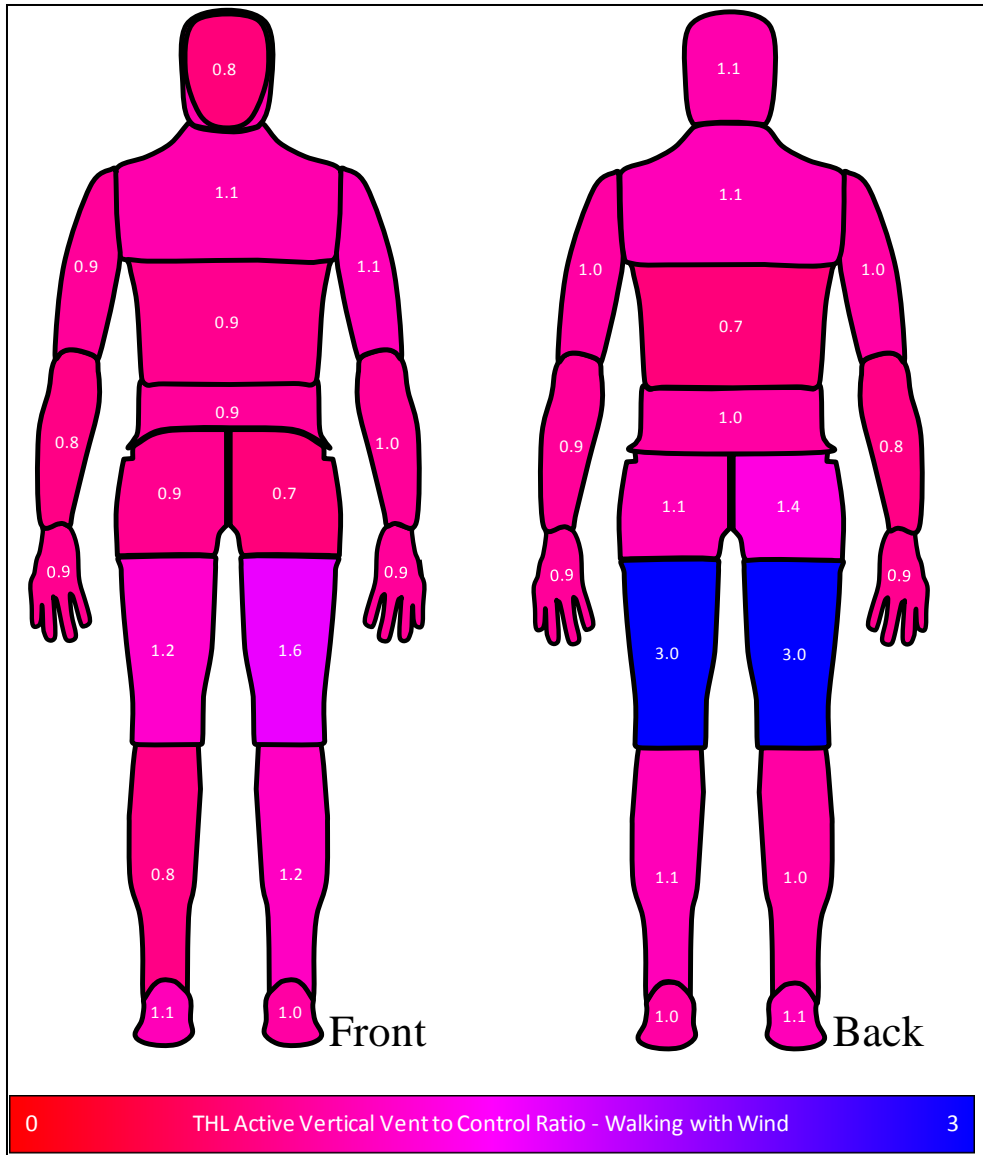


Figure 4-5. Active vertical vent THL ratio in dynamic test condition.

Both active ventilation designs showed statistically significant improvements in overall THL in the dynamic condition (17-21% increase over the control). However, the visual ratio depictions in Figures 4-4 and 4-5 indicate the majority of heat lost is isolated in

the lower body region. For the active zipper vents, there was little to no increase in THL in the upper arm region (0.9-1.3). This may be due to the standing posture of the manikin's arms and their tight placement close to the body's torso. In the legs, however, there us up to a 200% increase in heat loss. This follows the overall trend that more heat loss occurred in the trousers than the turnout coat for all ventilation designs, in all test conditions.

The same pattern is true for the active vertical vents in Figure 4-5. In the coat, there is little to no increase in ventilation (0.7-1.1). This lack of improvement is caused by the placement of the self-contained breathing apparatus (SCBA) as the manikin was dressed in a structural turnout ensemble. Further, there was a large overlap between the coat and the pants in the torso area, meaning any airflow through the coat did not reach the microclimate as it was covered by the trousers. In the back of the legs, however, where the vents were placed, there is a 300% increase in THL compared to the control.

These results further confirm the conclusions in Chapter 3, that pumping and forced convection are necessary to improve heat loss, especially with active vent designs. The majority of heat loss in this laboratory experimentation occurred in the trousers, or lower body region. The lack of heat loss in the turnout coat, or upper body region, may be due to the posture of the manikin. More than likely, it is due to the SCBA, as results in Chapter 3 demonstrate the detrimental effect this equipment has on air exchange. The SCBA not only closes off air movement between the microclimate regions within the suit, but also stifles air exchange through the suit to the external environment.

4.3 Virtual Modeling

4.3.1 Heat Stress and Heat Strain

Working in a hot, humid environment and performing substantial physical activity, with the addition of protective clothing, adds to the heat load on the body, causing a reduction in the temperature at which heat stress begins to occur (G. Havenith, 1999; McLellan & Selkirk, 2005). Heat stress refers to the specific heat load on the body coming from internal and external sources (Levine, Sawka, & Gonzalez, 1998; McLellan & Selkirk, 2005). The internal source of heat stress is generated by the body's metabolism and is a result of exercise intensity; external sources of heat stress come from the environment including the protective clothing worn (McLellan & Selkirk, 2005). Environmental factors such as, air temperature, humidity, and wind influence heat stress, along with clothing factors such as insulation and evaporative resistance of materials (I Holmér, 1995). Individual people produce heat and experience heat stress differently leading to a large variability in responses (G. Havenith & Van Middendorp, 1990; Levine et al., 1998).

The inability of the body to regulate and maintain core temperature at the necessary level is known as heat strain (Moran, Shitzer, & Pandolf, 1998). While heat stress refers to the environmental factors that cause the individual to store heat, heat strain refers to the physiological responses of the individual (Levine et al., 1998). When the body can no longer maintain a stable, comfortable core temperature heat strain begins to occur (Moran, Shitzer, et al., 1998). Thermal balance may be achieved at low levels of heat strain but as the thermal balance becomes positive, high internal core temperatures will be reached. A core temperature of at least 40°C is considered to be high (Sawka et al., 1992). However, once

core temperatures exceed 38° heat related illness or injury may occur (Teunissen, de Haan, de Koning, & Daanen, 2012). Heat illnesses, due to heat stress, may include cardiovascular strain, loss of fluids and electrolytes, and even heatstroke (Wenger et al., 2001). With each additional clothing layer, and as the activity level rises, the risk of heat strain increases (McLellan & Selkirk, 2005).

While core temperature is important for proper functioning of the body and must be regulated within a couple of degrees above or below 37°C, skin temperature is another physiological response which indicates the risk of a heat strain incident occurring. Skin temperature is important for heat exchange and is monitored by vasomotor control which raises or lowers the skin temperature to maintain thermal comfort. Thermal equilibrium is maintained at a skin temperature of approximately 33°C (Wenger et al., 2001). Skin temperature may fluctuate in a larger range than core temperature as it regulates the wearer's comfort and is affected by environmental conditions (G. Havenith, 1999). Differences between suits may be more pronounced when examining skin temperature as a parameter for physiological comfort, compared to core temperature.

Finally, sweat rates may be examined as a third parameter for physiological thermal comfort. According to Torii, who determined maximum sweat rates (SR_{max}) from multiple studies for marathon running in hot and cold seasons, after acclimatization sweating capacity reached a maximum of 2,000 g/hr (33 g/min) (Torii, 1995). This provides a benchmark range for sweat rate analysis.

Due to large variability between individual's physiological responses it is difficult to make generalizations regarding how people react to heat strain (G. Havenith & Van

Middendorp, 1990). Anthropometric measures may be predicted through the use of virtual modeling to determine the estimated core temperature, skin temperature, and sweat rate of the subject when wearing a particular clothing system. The major limitation of such a model is its prediction of the average population's response. Because predictive models use average values, people at extremes of the population distribution are put in danger (G. Havenith & Van Middendorp, 1990).

4.3.2 Experimental Methodology of Virtual Modeling

Time and expenses do not often allow for full human wear trial testing, or even manikin testing, in every environmental condition possible. Instead, thermoregulation, or physiological modeling, can be used to determine human response while wearing a particular garment in various temperatures and humid environments. There are many different thermoregulation models including those developed by Gordon et al. (1976), Konz et al. (1976), Wissler (1985), and Huizenga et al. (1999) (Fiala et al., 2001). Some of the best known and often used models include the Stolwijk, Fiala, and RadTherm® models.

RadTherm® was created by ThermoAnalytics® and is a heat transfer analysis software which predicts the body's transient heat transfer behavior including heat rates for radiation, conduction, and convection. The Human Thermal Module is an advanced plug-in for the software system that analyzes human comfort within complex environments (ThermoAnalytics, 2014). Localized thermoregulatory responses such as perspiration, respiration, activity level and blood flow changes are accounted for in this model. This model provides tools to improve clothing uniform and design by evaluating human comfort in different environmental scenarios. RadTherm® was built upon Fiala's work with the addition

of very small segments that predict specific heat transfer occurrence throughout the body, as seen in Figure 4-6.

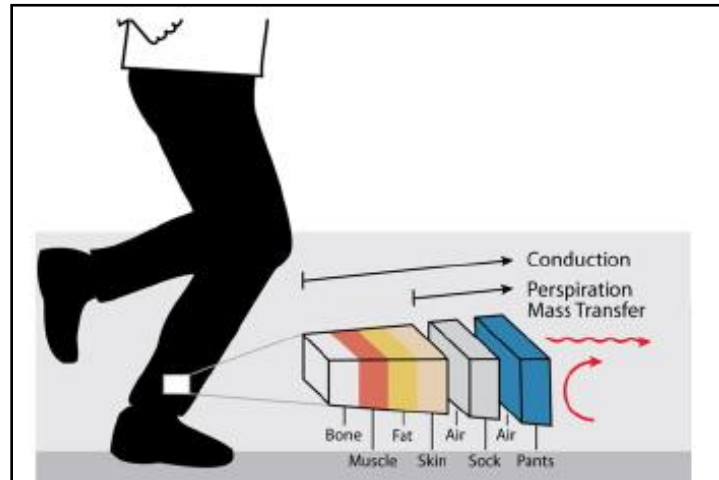


Figure 4-6. The prediction of mass transfer using the RadTherm Virtual Model (ThermoAnalytics, 2014).

The virtual human model has localized body segments where layers of clothing or equipment can be applied in specific regions (ThermoAnalytics, 2014). The RadTherm® model in particular, includes a clothing database with localized thermal and evaporative resistance data from over 100 scholarly articles (ThermoAnalytics, 2014). This aids in predicting complex, multi-layer garment designs with added equipment, such as firefighter turnout gear. This system incorporates multiple technologies to predict the skin, core body, and clothing temperatures along with different sized humans based upon height, weight, and ethnicity (ThermoAnalytics, 2014). This model is one of the most comprehensive of its kind.

For use in this study, the thermal insulation and evaporative resistance values from the sweating manikin were entered into the RadTherm® model for each section of the body. A specific temperature and relative humidity setting was used to simulate a vehicle extrication condition. Once all parameters are input into the software program the model simulates core body temperature (hypothalamus and rectal), skin temperature, and sweat rates over the course of the protocol time period. Physiological heat strain responses from the model can be used to determine the relationship between THL values on the sweating manikin and their impact on physiological comfort. Table 4-1 below includes the detailed physiological modeling protocol used for this study.

Table 4-1. Physiological modeling extrication protocol.

Temperature (°C)	Relative Humidity	Length of Protocol	Activity Level	Activity Type
21	50%	90 minutes	4 Mets	Standing

Based upon the initial THL results from the sweating thermal manikin in Chapter 3, the passive open vent, active zipper vent, and active vertical vent turnout designs were chosen for further analysis to investigate their implementation into prototypes for heat strain reduction. These three vented suits, along with the standard control turnout, were modeled according to the protocol in Table 4-1 above to determine if any differences in physiological comfort existed. The thermal and evaporative resistance values of each suit, in each of the four test conditions, were entered into the RadTherm® Human Thermal Model. Predicted

physiological responses between the suits were used to further down select ventilation designs for implementation into structural firefighter turnout prototypes for testing on the human wear level.

Statistical significance for virtual heat strain modeling was determined by analyzing if each data point fell within two standard deviations of the sample mean. This method of determining statistical significance was limited by the lack of repeated measures inherent to the modeling methodology.

4.3.3 Results and Discussion of Virtual Modeling

Core temperature (T_{hyp}), skin temperature (T_{sk}), and sweat rate (SR) were predicted using the human thermal model. It should be noted the predicted hypothalamus core temperature (T_{hyp}) values were analyzed in this study, as opposed to the rectal core temperature (T_{rec}) predictions. Models were conducted using the thermal and evaporative resistance data from all four test conditions. The predicted physiological responses from virtual modeling of the four suits are shown in Table 4-2 below. The data points given in the table reflect end point, total body average results, at the completion of the 90 minute protocol.

Table 4-2. Overall ventilation modeling results.

Condition	Suit	T_{thy} (°C)	T_{sk} (°C)	SR (g/min)
Standing with still air	Control	40.05	39.57	30
	POV	39.64	39.08	30
	AVV	40.11	39.67	30
	AZV	40.14	39.69	30
Walking with still air	Control	38.71	37.78	27.79
	POV	38.15	36.67	17.16
	AVV	38.53	37.5	24.23
	AZV	38.21	36.8	18.32
Standing with wind	Control	39.2	38.48	30
	POV	38.1	36.56	16.11
	AVV	38.89	38.06	29.99
	AZV	39.22	38.5	30
Walking with wind	Control	38.3	37.04	20.83
	POV	37.97	36.01	12.89
	AVV	38.14	36.63	16.96
	AZV	38.18	36.73	17.77

*POV = Passive Open Vent; AVV = Active Vertical Vent; AZV = Active Zipper Vent

The results in Table 4-2 reflect the impact of increased ventilation on the physiological comfort of the wearer. It is well known that forced convection through air movement (wind) and body motion (walking) increases ventilation (Bouskill, Havenith, Kuklane, Parsons, & Withey, 2002; Dai & Havenith, 2009; G. Havenith & Nilsson, 2004; Ruckman et al., 1998; Xiang Hui Zhang & Li, 2011). It is not completely understood, however, how an increase in ventilation impacts the physiological responses of the body, especially in structural firefighter turnouts.

In the standing with wind condition, differences between suits are most pronounced, particularly between the control and POV. Here a reduction in THL of 70 W/m² corresponds to a drop in predicted core temperature of over 1°C, a decrease in predicted skin temperature

of almost 2°C, and a reduction in predicted sweat rate of 13.9 g/min. As wind and body motion were introduced into the testing environment the predicted core temperature, predicted skin temperature, and predicted sweat rate decreased, compared to the standing with still air condition. This was true for all turnouts, regardless of whether ventilation openings were present or not.

Figure 4-7 illustrates the average predicted core temperature for each suit over the 90 minute modeling protocol when the thermal and evaporative resistance data was taken from the dynamic (walking with wind) test condition. When walking and wind data was modeled, the largest reduction in overall predicted core temperature was measured, compared to the static condition. Differences between suits followed a similar trend in each test condition with the control having the highest predicted core temperature, followed by the two active vents, and the POV with the lowest. These differences, however, were the least pronounced in the dynamic condition. As forced convection continues to rise, there is an upper limit at which ventilation is no longer increasingly beneficial as it has reached its maximum potential. Therefore, all four suits had a significantly lower predicted core temperature in this condition, compared to the static. The POV suit, however, did show a decrease by 0.3°C, compared to the control, in this condition.

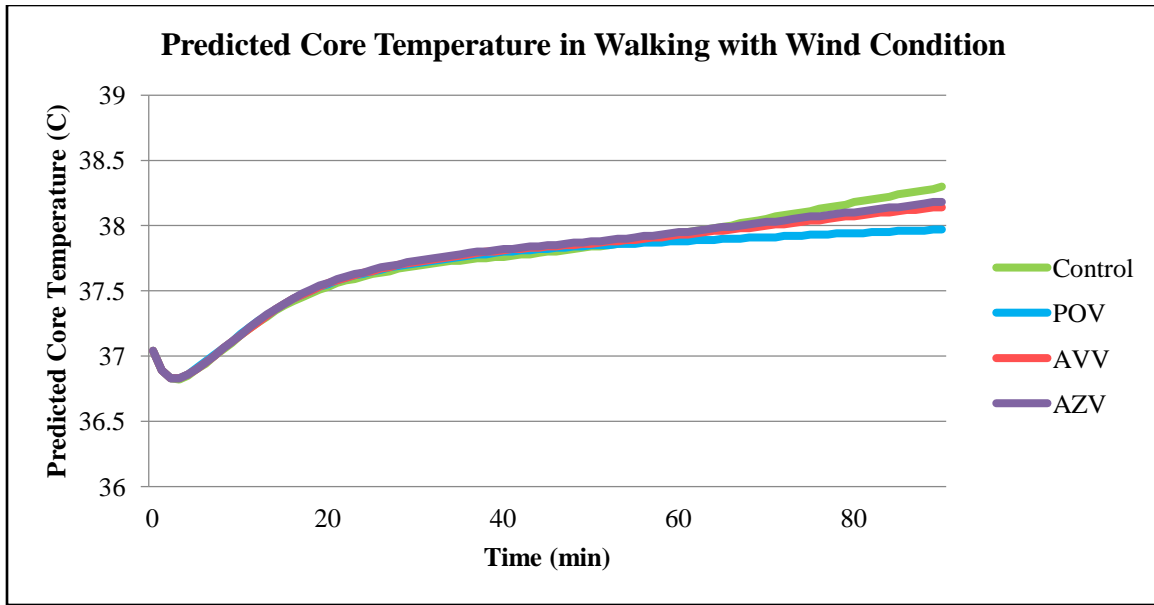


Figure 4-7. The predicted average body core temperature for each suit using walking with wind test condition data in the physiological model.

When the standing with wind resistance data was modeled, the difference between the POV suit and Control was even further pronounced by a drop in predicted core temperature of 1.1°C. Based upon data from the literature, this is both statistically significant, as well as meaningful for the wearer's physiological comfort. Further, there was a 0.3°C drop in predicted core temperature for the active vertical vent (AVV) suit. There was no difference between the control and active zipper vent (AZV) suit.

In the walking with still air condition, the overall predicted core temperature of each suit was significantly reduced, compared to the standing with still air condition, and differences were slightly more pronounced. There was a 0.5°C drop in predicted core

temperature for the POV but no significant differences were detected between the Control and the two active vents.

There is little to no difference in predicted core temperature between suits in the standing with still air condition until approximately the 40 minute mark, at which time the passive open vent (POV) suit does not continue to rise along with the others. Overall, the wearer in this suit had an end value predicted core temperature 0.4°C lower than the control or active vent suits. This indicates a meaningful impact on the wearer's detection of improved comfort. Hence, the need for further human wear level testing to confirm such a conclusion.

Figure 4-8 shows the correlation between the maximum predicted rise in core temperature throughout the protocol and the overall average THL measured on a sweating thermal manikin in the walking with wind condition. These results demonstrate a strong correlation ($R^2 = 0.95$) between increases in heat loss in the clothing system and decreases in the predicted core temperature of the wearer. In the walking with wind test condition, the POV had an increase in THL of 52 W/m² which correlates to a predicted reduction in core temperature of over 0.3°C. In the standing with wind condition, the POV had an increase in THL of over 70 W/m² resulting in a 1.1°C drop in predicted core temperature. It should be noted, the strong correlation between variables is not surprising due to the raw resistance data from THL measurements being used in the RadTherm® model to predict physiological responses.

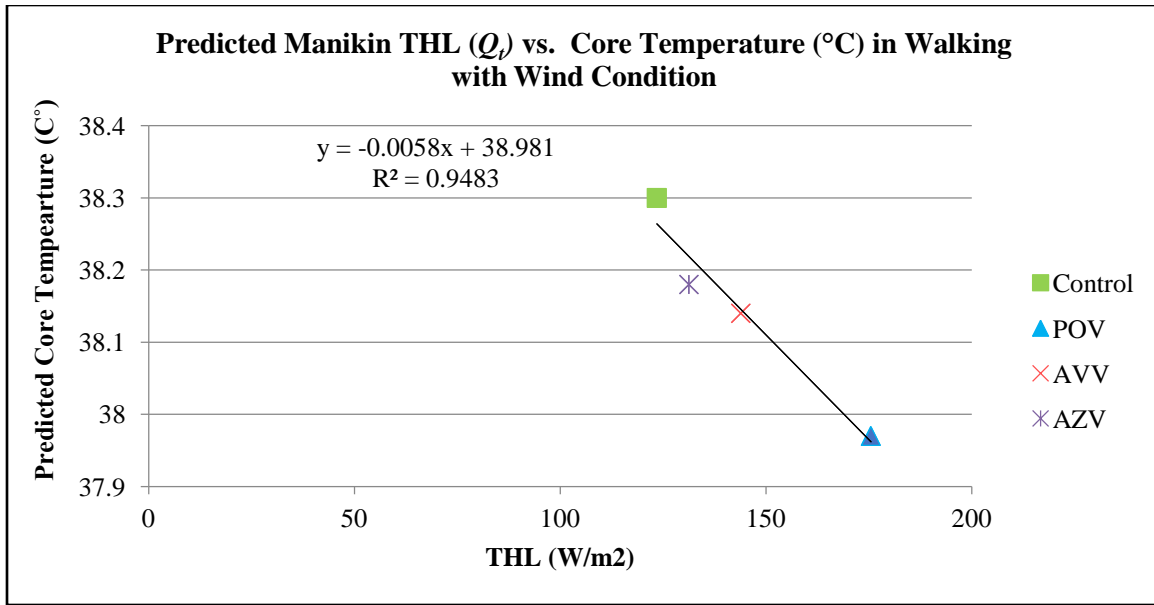


Figure 4-8. Correlation between the predicted core temperature and the average THL for each suit in the walking with wind condition.

Skin temperature was modeled for each suit in all four test conditions as well. Figure 4-9 depicts the predicted skin temperature responses for each suit, using the walking with wind resistance data, in the same 90 minute extrication protocol. In this condition, the POV suit had an end point predicted skin temperature at 90 minutes that was 1.0°C lower than the Control. The AVV and AZV had predicted skin temperatures that were 0.4°C and 0.3°C lower than the Control, respectively.

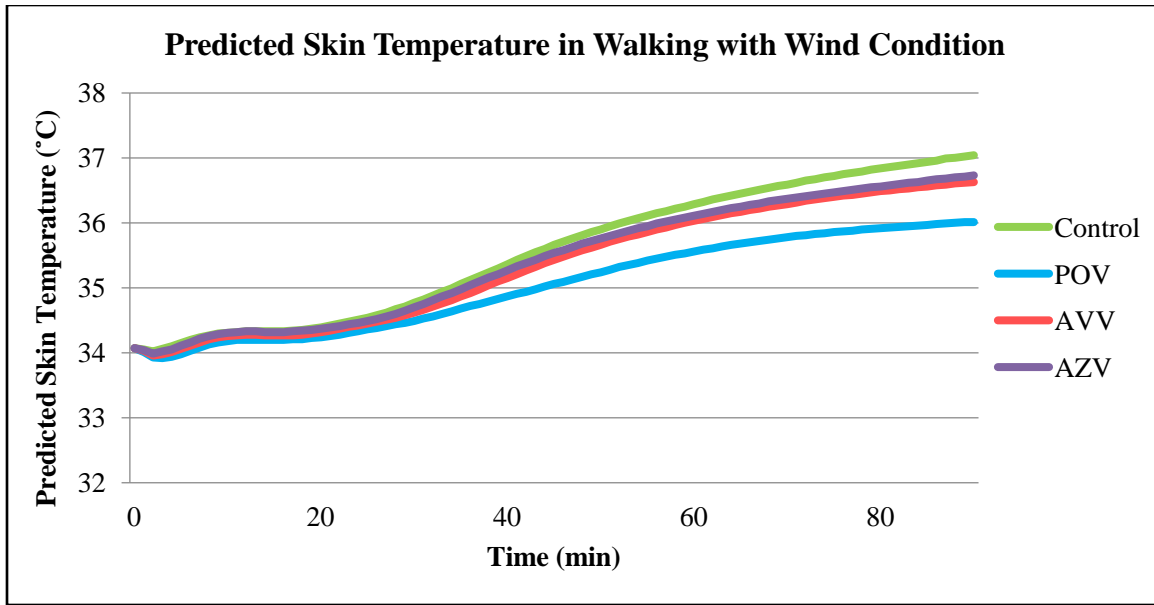


Figure 4-9. The predicted average skin temperature for each suit using walking with wind test condition data in the physiological model.

Differences in predicted skin temperature were most pronounced in the standing with wind condition. In this condition, the largest reduction in THL was measured for the POV suit with a reduction of 70 W/m^2 compared to the Control. This led to a 1.1°C drop in predicted core temperature and 1.9°C reduction in predicted skin temperature. Both the POV and AZV suits had a 1°C reduction in predicted skin temperature in the walking with still air condition. In the static condition, the only significant change in skin temperature occurred in the POV suit (-0.49°C). Overall, as walking and wind were added to the environmental conditions, predicted skin temperature for all suits was reduced. The skin temperature data also reflects an improvement in physiological comfort when ventilation openings are added to structural turnouts, especially for the POV suit.

Sweat rates in the RadTherm® model are not given past a maximum of 30 g/min. In the standing with still air condition, all four suits reached the 30 g/min maximum sweat rate before the conclusion of the 90 minute protocol, indicating the severity on the physiological condition of the wearer. When the walking with still air data was modeled, the POV (17.2 g/min) and AZV (18.3 g/min) suits had a 10 g/min predicted reduction in sweat rate compared to the control. Differences between suits were greatest in this condition. For the standing with wind condition, the control suit was predicted to reach the maximum sweat rate 59 minutes into the protocol, whereas, the POV suit only reached a predicted sweat rate of 16.1 g/min by the end of the 90 minute protocol. Figure 4-10 illustrates the walking with wind data which reflected the lowest predicted sweat rates at just 20 g/min for the control compared to 12.9, 17.0, and 17.8 g/min for the POV, AVV, and AZV suits, respectively. Charts illustrating the predicted core temperature, skin temperature, and sweat rates for the static, walking with still air, and standing with wind test conditions can be found in Appendix B.

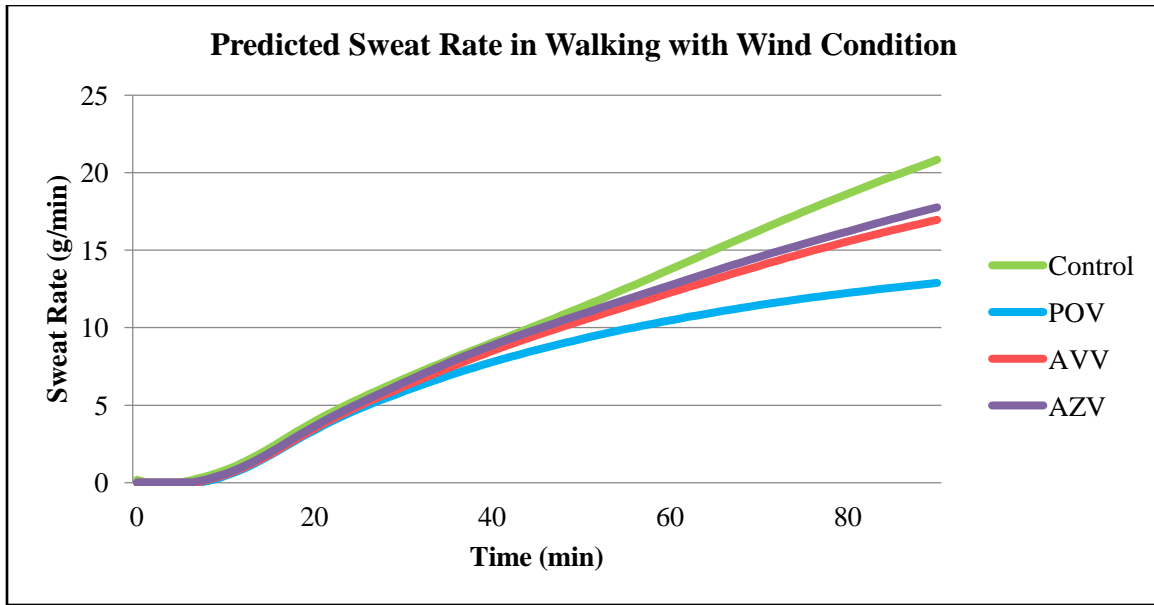


Figure 4-10. The predicted average sweat rate for each suit using walking with wind test condition data in the physiological model.

4.4 Estimated Ventilation Calculations

Thus far, all ventilation results, including those modeled, have been derived from thermal insulation and evaporative resistance data conducted on a sweating thermal manikin to determine overall THL for each suit and localized zones. Traditionally, direct ventilation (L/min) would be measured using a tracer gas dilution method. Due to limited time and resources, as well as scope, it was not possible to conduct such measurements in this study. Further, heat loss measurements are directly related to the body's thermal comfort and can be modeled to determine the wearer's physiological responses, a limitation to the tracer gas method. Instead, calculations were completed from the raw thermal resistance data to determine an estimated ventilation rate, traditionally measured by the tracer gas method,

known as the Ventilation Index (V). Further information regarding this method can be found in Chapter Two, sections 2.2.2 and 2.2.3.

4.4.1 Methodology of Ventilation Calculations

The average thermal resistance (R_t) values for each of the four suits (Control, POV, AVV, and AZV) were used to estimate the Ventilation Index (V). Based upon the properties of ventilation (air density, heat capacity, and body surface area), a change in V can be equated to a change in h , the heat transfer coefficient. Assuming ΔV is equal to Δh , ventilation was estimated according to Equation 4.2:

Equation 4.2 Estimated Clothing Ventilation

$$V = \frac{\Delta h * A_{body}}{\rho c}, \text{ where:} \quad (4.2)$$

V = ventilation (m^3/sec , or 60,000 liters/min/ m^2),

Δh = change in heat transfer coefficient ($\text{W}/\text{m}^2\text{K}$), between conditions,

A_{body} = average surface area of the test manikin (m^2),

ρ = air density ($1.2041 \text{ kg}/\text{m}^3$), and

c = specific heat capacity of the body ($1 \text{ J}/\text{gK}$).

Based upon literature, the relationship between ventilation and the change in heat transfer in Equation 4.2 may be simplified through the conversion of units to depict total ventilation (liters/min) over the body surface area (m^2) which is reflected in Equation 4.3 below.

Equation 4.3 Simplification of Equation 4.2

$$\frac{V}{A_{body}} = \Delta h * 50, \text{ where:} \quad (4.3)$$

V = ventilation (liters/min/m²),

A_{body} = average surface area of the test manikin (m²), and

$\Delta h = \frac{1}{I_{tot\ walk/wind}} - \frac{1}{I_{tot\ static}}$, the inverse of the difference between thermal resistance

in a forced convection condition and a static condition where,

I_{tot} = total thermal resistance (insulation) of the clothing and surface air layer around the manikin (m²/W).

It should be noted that the values calculated from these equations are approximate estimations of the Ventilation Index (V) and not exact values acquired from actual test measurements. Only the thermal resistance values were used to conduct these estimations, therefore it is not a complete depiction as evaporative resistance was not taken into account. The same estimations were conducted using the evaporative resistance data but due to increased variability and scope, are not included in the dissertation document. Assumptions of this equation are that the microclimate heats up completely, assuming 100% capacity. It is likely the approximated values underestimate actual ventilation because it only captures that which is associated with dry heat loss. An advantage of using the sweating thermal manikin method and then estimating the Ventilation Index is that it allows for analysis of isolated zones within the clothing system. Here, the average ventilation over the entire manikin surface (1.8 m²) was calculated, however, it is possible to conduct ventilation estimations for each of the 34 individualized zones.

Statistical significance for the clothing ventilation estimations was determined by analyzing if each data point fell within two standard deviations of the sample mean. This

method of determining statistical significance was limited by the lack of repeated measures inherent to the ventilation estimation methodology.

4.4.2 Results and Discussion of Estimated Ventilation Calculations

Ventilation estimates were calculated for the Control, POV, AVV, and AZV suits in each test condition (walking with still air, standing with wind, and walking with wind) as compared to the standing with still air thermal resistance data. Table 4-3 gives the Ventilation in L/min/m² for each suit in each condition, along with the overall measured THL (W/m²) and predicted core temperature (°C).

Table 4-3. Estimated ventilation rates of ventilated turnouts.

Condition	Suit	Ventilation(V) (l/min/m2)	THL(Q _t) (W/m ²)	Core Temp (°C)
Walking	Control	32.37	103.2	38.71
	POV	59.19	145.7	38.15
	AVV	61.56	122.4	38.53
	AZV	62.85	125.1	38.21
Wind	Control	33	91.3	39.2
	POV	76.61	161.5	38.1
	AVV	40.98	95.6	38.89
	AZV	32.72	90.9	39.22
Dynamic	Control	67.04	123.5	38.3
	POV	97.61	175.5	37.97
	AVV	82.9	143.9	38.14
	AZV	77.8	131.3	38.18

*POV = Passive Open Vent; AVV = Active Vertical Vent; AZV = Active Zipper Vent

Results in Table 4-3 demonstrate the improvement in air flow through the clothing system due to ventilation openings placed in structural turnouts. In each test condition, the

ventilation estimates ($l/min/m^2$) for the three vented suits are significantly greater than the control garment. These differences are most pronounced for the POV suit in the wind condition. There was a $70 W/m^2$ increase in THL and a $1.1^\circ C$ drop in predicted core temperature, which is estimated to lead to a 57% increase in ventilation. In the walking with wind condition, ventilation was improved by 31.3%, 19.1%, and 13.8% for the POV, AVV, and AZV suits, respectively.

These estimations confirm the improvement in heat loss when ventilation openings are added to the clothing system. Figure 4-11 illustrates the strong correlation ($R^2 = 0.84$) between ventilation estimates and manikin THL values in the three test conditions where forced convection was present, either through wind or walking, or both. Because the ventilation estimation values are derived from the raw thermal resistance data, correlations between THL and V are strong, however, it is not a perfect correlation because the evaporative component is not taken into consideration.

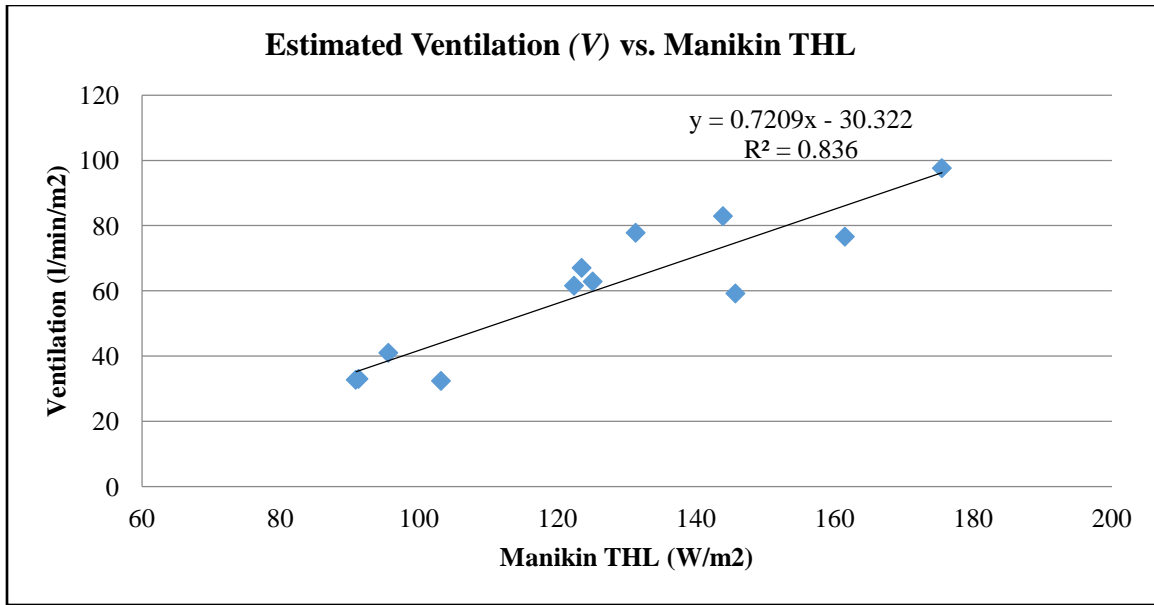


Figure 4-11. Correlation between the estimated ventilation (V) and the average manikin THL for each suit in the forced convection test conditions.

As discussed in Chapter Two, section 2.2.2., the ventilation index (V) can be used as a quantitative rating scale that enables comparisons between garments to be made. The required ventilation (liters/minute) necessary in various clothing types with specified activity levels and wind speeds is given (Birnbaum & Crockford, 1978). According to Birnbaum and Crockford, a ventilation rate of approximately 78 L/min is required for walking at two miles/hour. General firefighting activities require 8 Mets of work, according to the 2011 Compendium of Physical Activities (“Compendium of Physical Activities,” 2011) which equates to running at five miles/hour. Therefore, firefighters would need clothing systems that provide at least 78 L/min of ventilation (see figure 2-2), if not greater in conditions where no wind is present. The results above show that even when forced convection through

walking and wind is added, the maximum ventilation (V) achieved is 97.6 L/min/m². This relationship indicates using this method as an additional tool in analyzing heat loss data is valid and beneficial for comparing turnout prototypes to other types of functional and protective clothing. Further analysis is necessary, however, to determine if the measured differences in heat loss create a meaningful impact on the firefighter's measured physiological responses.

4.5 Conclusions

It is evident the addition of ventilation openings in clothing not only improves heat loss, as was demonstrated in Chapter Three, but also leads to isolated microclimate ventilation improvements, increased physiological comfort, as well as, additional air flow within the microclimate of the suit (i.e. ventilation). The alternative methodologies described in this chapter included: manikin THL ratios to examine individual zones of the turnout system and how vent openings in those areas impacted isolated heat loss, human thermal modeling to predict the firefighter's physiological responses when wearing each ventilated suit, and estimations of direct ventilation, or air flow (L/min), created by the addition of ventilation openings. Correlations between THL and predicted core temperature ($R^2 = 0.95$), as well as estimated ventilation ($R^2 = 0.84$), were strong. This is likely due to the use of the raw THL data (thermal insulation and evaporative resistance) to conduct the human thermal modeling and estimate ventilation (use of thermal insulation values only).

Isolated manikin zone THL ratios provided an additional tool for analyzing the placement of vent openings in turnouts and the corresponding heat loss measured. Results in Chapter 3 demonstrated the majority of heat loss occurred in the pants and lower body region

than in the turnout coats. This was easily depicted by the isolated zone ratios compared to the traditional numerical THL graphic. Using these ratios as an additional tool for analyzing heat loss data assists the researcher in quickly identifying areas of the garment where the greatest heat loss occurred, as well as recognizing areas where limitations exist, such as the placement of the SCBA and its impact on reduced air flow in the turnout coat.

Estimated ventilation results showed that even when forced convection through walking and wind is added, the maximum ventilation (V) achieved is 97.6 L/min/m². This was for the POV suit, which was a maximalist approach toward venting, which would not be realistically feasible for complete adoption into commercial turnouts due to its decrease in thermal and chemical protection. However, this may reflect a limitation of the estimated ventilation calculations as they do not take into consideration the evaporative resistance, or wet heat loss component, which is often times the greatest contributor towards heat loss in the clothing system. This method does demonstrate the potential for achieving heat loss and ventilation in turnouts, which was the primary objective of this research.

Differences in heat loss and ventilation between suits indicate large improvements but, it cannot be determined from this analysis alone whether it would provide a significant impact on the wearer's detection of improved comfort. Hence, the need for further human wear level testing to confirm such a conclusion. Overall, results from these alternative methodologies provide a more in-depth analysis of ventilation in the turnout system which gives designers and manufacturers additional tools in the product development process. The knowledge generated from this experimentation confirms the choice of clothing ventilation design modifications when developing final prototypes (see Chapter Eight).

*Portions of the research presented in this chapter have been accepted for publication in the 2016 ASTM Selected Technical Papers (McQuerry, Barker, DenHartog, & Hummel, 2016).

5 Analysis of Clothing Bulk in Structural Firefighter Ensembles and its Impact on Heat Stress

5.1 Introduction

Beyond clothing ventilation openings, issues of additional materials, or "bulk," need to be further explored. In recent decades, the number of burn injuries has been drastically reduced thanks in part to the addition of multiple layers and thicker materials in the turnout composite. On the other hand, incidents related to fatigue, exhaustion, heat strain, and fatalities from cardiovascular strain have risen. The multi-layer fabric construction of firefighter turnouts reduces the ability of heat loss to occur by creating a humid microclimate and multiple air gaps, which increase clothing insulation. Current structural turnouts severely reduce heat exchange through sweat evaporation (Ingvar Holmér, 2006) as more layers are added to achieve higher levels of protection for the worst case scenario, such as a flashover or back draft. Increased thickness has been added in the form of extra thermal liner layers. These thick, nonwoven batting layers are placed close to the skin and trap both air and moisture near the body. By increasing thermal protection, heat stress issues have been exacerbated as evidenced by increased cases of impaired performance, illness, collapse, and even death (Nunneley, 1989).

In addition to the three layer base composite, extra layers are added for increased protection in specific areas of the garment. These extra layers are known as reinforcements and are used to provide additional insulation, absorb shock, and protect primary clothing layers (J. O. Stull & Stull, 2009). Examples include foam composites and leather padding which are required in the shoulder and knee regions. Extra materials are added in these areas

because they are contact points during kneeling and crawling. The shoulder area is also where the SCBA rests. While firefighters do need extra protection in certain areas of the suit, multiple thermal liner layers all over the body can be overkill. These additional layers create more air gaps leading to higher levels of thermal protection (J. O. Stull & Stull, 2009) and decrease the ability of heat loss to occur. Unfortunately, additional thermal barrier layers are the most common type of reinforcement (J. O. Stull & Stull, 2009).

An increase in weight is also a concern as more materials are added to the turnout ensemble. Firefighters often add an additional 70 pounds or more, depending upon the tools they may be carrying, when donning the full structural ensemble (The Haddam Volunteer Fire Company, 2013). The total weight of the turnout ensemble consists of the coat, pants, helmet, hood, gloves, boots, and SCBA system, along with any additional tools needed for the job (The Haddam Volunteer Fire Company, 2013). On average, the base ensemble is approximately 45 pounds, however, adding tools, such as a thermal imaging camera, radio, and light, can increase the weight to almost 75 pounds (The Haddam Volunteer Fire Company, 2013). Turnout ensemble weight increases further when coats and trousers become soaked from putting out a fire. Extra weight adds to an already bulky turnout and requires even more effort for the wearer to move and perform physical activity, placing more stress on the body. Therefore, a strategic reduction of bulk within the turnout clothing system should be evaluated for reducing heat stress.

5.2 Experimental Methodology

Structural firefighter turnouts on the market today come in a variety of shapes and sizes. Some turnout designs meet the bare minimum for NFPA 1971 compliance while others

bulk up for extreme protection according to their department's firefighting tactics. To determine how added bulk affects heat stress and heat loss, suits with varying levels of additional materials, reinforcements, and layers were evaluated.

A set of four garments were tested including: 1) a lightweight suit with minimum reinforcements 2) a standard control suit, 3) a heavy duty suit and 4) a passive vent suit. The lightweight suit had the bare minimum accessories and additional layers in order to be NFPA 1971 compliant. It did not include pockets, extra patches, or leather reinforcements. A standard turnout garment, used as the control suit throughout the entire study, was also evaluated. It did contain the standard number and types of reinforcements including leather reinforcements in the shoulders and knees, vented trim, and additional padding in the required areas. A heavy duty suit was tested which incorporated thick, foam composites in the upper chest, back, shoulders, and arms for additional thermal protection. This suit had a wider collar and a specially designed three-layer hood, or balaclava. Last, a suit designed with a heat relieving passive vent was evaluated. An additional thermal liner was placed inside the chest and arm areas of this suit, similar to the heavy duty suit, but not as thick as the foam composites. A small vent was placed in the torso region of the moisture barrier within this suit to relieve heat stress by increasing moisture exchange. Figure 5-1 below illustrates these four suits.



Figure 5-1. Suits tested with varying levels of bulk.

Each of the suits above was tested for THL on a sweating thermal manikin (see section 3.2.2 for test methodology) in a static condition with a standing manikin and still air movement at 0.4 m/s. Thermal and evaporative resistance measurements were further analyzed by using RadTherm® thermal modeling software from ThermoAnalytics (see section 4.3.2). This virtual modeling tool provided predictive physiological responses (core temperature, skin temperature, and sweat rates) of a firefighter, given specified environmental conditions and work rate. An evaluation of the weight of the turnout ensemble was taken using the standard control suit. The level of bulk of each suit was determined by a base composite layering analysis. The number and location of layers in each suit was calculated and illustrated. A software analysis tool was used to determine the percentage of base composite for each suit. All materials were held constant throughout this research study. Table 5-1 provides material and weight details for each of the four turnouts tested.

Table 5-1. Reduction of bulk testing suit materials and weight details.

Suit	Outer Shell	Moisture Barrier	Thermal Liner	Weight of Coat & Pants (lbs)
Control	PBI Matrix	Crosstech/Aramid Quilt	Caldura SL 2 Layer	10.10
Light Weight				8.56
Heavy Duty				10.68
Passive Vent				11.90

The standard control suit composite and additional reinforcements were evaluated for THL on the fabric level. This testing gives an evaluation of heat loss for each section, or area, of the suit where added materials and layers affect the amount of heat loss which can occur. TPP was also performed on the control suit composite to determine areas of the suit where the minimum requirement of a 35 TPP value was met or exceeded when reinforcements are added (NFPA, 2013). Table 5-2 details the garment areas evaluated for both THL and TPP on the fabric level. Thickness measurements of each composite with additional reinforcements were completed in order to correlate with THL and TPP results on the fabric level.

Table 5-2. Fabric level TPP and THL test configurations.

Material Tested	Garment Component	Number of Layers
Base Composite	Base Composite	3
Base + Base	Coat & Pant Overlap	6
Base+Foam+Leather	Knee & Shoulder Areas	5
Base + Outer Shell	Pocket	4
Base + OS + OS	Pocket Flap	5
Base + Label	NFPA Label Overlap	4
Base + Trim	Trim Overlap	4
Boot Composite	Boot	3
Base + Boot	Boot & Pant Overlap	6

5.2.1 Procedures

5.2.1.1 Thermal Protective Performance (TPP)

Thermal protective performance measures the time it takes for a second-degree burn to occur when wearing personal protective equipment. This test was developed by DuPont in the 1970s to set realistic conditions for combined radiant and convective heat exposure during firefighting (DuPont, 2014b). TPP tests take into account both the amount of time that elapses and the amount of heat energy per surface area required for temperature and energy to be transferred to the back of the fabric being tested (DuPont, 2014b; NFPA, 2013). Three fabric samples (6 in. x 6 in.) were tested according to a real fire simulation with a constant combination of 50% radiant and 50% convective heat at a constant heat flux of 84 kW/m^2 (DuPont, 2014b). The test apparatus is specified in the International Standards Organization (ISO) standard 17492 (NFPA, 2013). TPP testing is required by NFPA 1971 for structural firefighter protective clothing which must have a TPP value no less than 35 cal/cm^2 for coats

and pants (NFPA, 2013). TPP ratings for each individual specimen should be recorded and an average TPP rating calculated for each sample (NFPA, 2013). If a TPP rating is greater than 60, it is reported as, ">60".

5.2.1.2 Total Heat Loss (THL) on a Sweating Guarded Hot Plate

Total heat loss testing measures both dry and wet forms of heat transfer, on the fabric level, using a sweating guarded hot plate which simulates how heat transfers through skin (Globe Manufacturing, 2015b). Dry testing simulates convective heat loss to the external environment, which results from the temperature gradient, while wet testing simulates evaporative heat loss, which is due to the vapor pressure gradient (Globe Manufacturing, 2015b). Total heat loss is a combination of the dry and wet heat loss of the three layer base composite materials.

THL testing was first introduced for structural firefighting protective elements in NFPA 1971, 2000 edition with a minimum THL requirement of 130 W/m^2 . This value was raised to 205 W/m^2 in the 2007 revision and remains in the latest 2013 edition (Globe Manufacturing, 2015b). This test evaluates structural firefighter base composite materials which consist of the outer shell, moisture barrier, and thermal liner layers.

Three fabric samples (20 in. x 20 in.) were evaluated using ASTM F 1868-14 *Standard Test Method for Thermal and Evaporative Resistance of Clothing Materials Using a Sweating Hot Plate*, with modifications (NFPA, 2013). These modifications include: placing the side normally facing the human body directly on the test plate, arranging the layers in the order and orientation as worn, smoothing each layer out by hand to avoid wrinkles, and making no further adjustments once the test has begun (NFPA, 2013). The

average intrinsic thermal resistance (R_{cf}) and evaporative resistance (AR_{cf}) are recorded for each sample. The average total heat loss (Q_t) is calculated for each sample. The specimens pass or fail based upon the $205 \text{ W/m}^2 Q_t$ requirement.

THL results typically have an inverse relationship with TPP ratings. TPP is a measure of protection, with thicker and heavier materials providing higher TPP ratings, while THL is a measure of breathability, with lighter and thinner materials providing a higher THL (Globe Manufacturing, 2015a). In order to obtain higher TPP ratings, the insulation of the fabric ensemble must be increased, while the opposite is true for THL, in which insulation must be decreased in order for heat to escape (Globe Manufacturing, 2015b). The values of each test must be optimized for comfort and protection to be maintained in the clothing ensemble.

The limitation of both TPP and THL tests specified in NFPA 1971 is their inability to take garment construction and design into consideration. These tests are a function of the fabric materials in the three layer system only, and do not consider the addition of padding, trim, labels, pockets, and reinforcements. Therefore, systems level testing should also be performed.

THL on a sweating thermal manikin was also conducted on the set of four turnouts with varying levels of thickness and layers. The methodology for this test method can be found in Chapter 3, section 3.2.2, "Total Heat Loss (THL) on a Sweating Thermal Manikin." Similarly, the methodology for the virtual modeling that was conducted can be found in Chapter 4, section 4.3.2.

5.2.2 Statistical Analysis

To determine the statistical significance of the measured differences in predicted manikin THL, compared to the baseline control, two-sample t-tests, assuming equal variances, were performed using Minitab statistical software, version 16. All data was tested for normalcy and normal distributions were confirmed through a probability plot and the Anderson-Darling test statistic. A one-way ANOVA was conducted to determine if significant differences were present. If differences were identified between the results, t-tests were carried out. A p-value less than 0.05 indicates a significant difference in THL between the turnouts.

The thickness of each garment component, tested on the fabric level, was measured and correlated with the TPP and THL results. Correlations were established between thickness and TPP, as well as, thickness and THL to determine how bulk affects heat loss and thermal protection. The coefficient of determination (r^2) was used to determine the strength of the relationship between variables and how well the regression line represents the data. The closer r^2 is to 1, or 100%, the greater the model's ability to explain the variability of the response data.

Statistical significance for the virtual heat strain modeling was determined by analyzing if each data point fell within two standard deviations of the sample mean. This method of determining statistical significance was limited by the lack of repeated measures inherent to the modeling methodology.

5.3 Results

The addition of weight plays a vital role in the heat stress a wearer experiences. The weight of each component in a structural firefighter turnout ensemble was taken using the study's control turnout. The helmet, hood, SCBA, SCBA mask, coat, base layers, gloves, trousers, and boots were weighed individually. The percentage of weight of each component in the full turnout ensemble is illustrated in Figure 5-2 below.

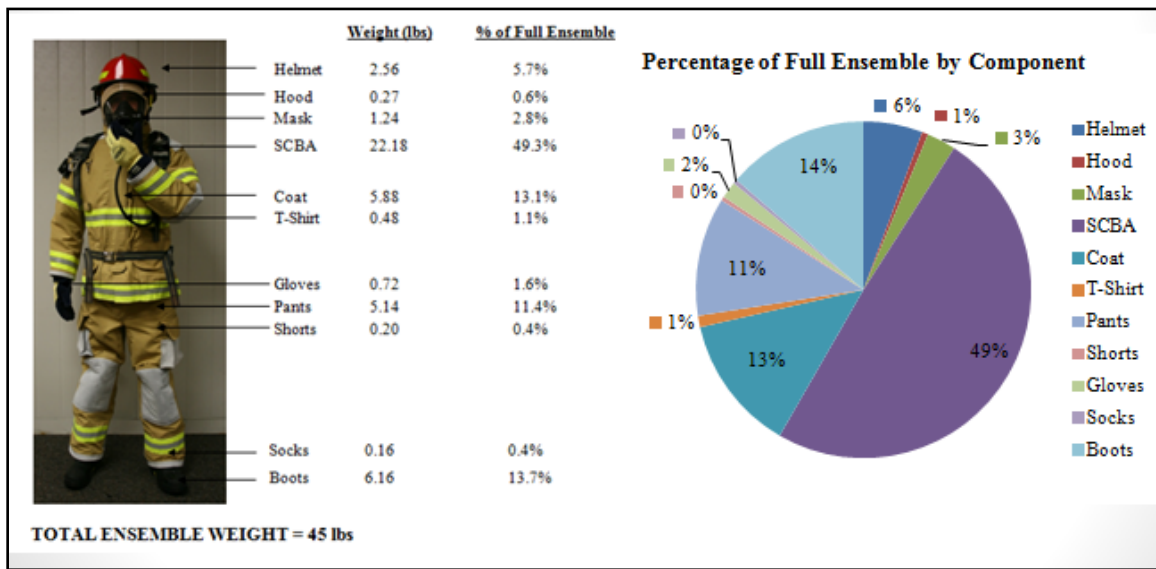


Figure 5-2. Weight distribution of firefighter turnout ensemble.

The SCBA makes up almost 50% of the entire turnout ensemble's weight, even more so when the air tank is full. The next heaviest items were the boots at 6.16 lbs, followed by the turnout coat and pants, at 5.88 lbs and 5.14 lbs, respectively. This demonstrates the impact the coat and pants contribute to the overall physical load added to the wearer when

donning the clothing ensemble. As two of the heaviest items the firefighter wears, the coat and pants lead to heat stress quickly when being worn during heavy physical activity in hot environments.

5.3.1 Base Composite Layering Analysis

A base composite analysis was performed as a measurement of the level of bulk in terms of the number of additional layers for each of the four turnouts evaluated. The number of layers in each area of the garments was calculated and illustrated using a software illustration package. From this, the percentage of the garment consisting of the base composite only, with no additional layers, was calculated. Of the four suits evaluated, the light weight suit, with no pockets or added accessories, had the greatest base composite percentage of all four suits at 53.8% overall. About half of the control suit consisted of base composite area only, followed by the passive vent suit with only 37.6% base composite. The heavy duty suit had the least amount of area consisting of only the base composite at just 33.3%. Base composite percentages were calculated for each individual garment as well, including the front and back of each coat and pant. Figure 5-3 illustrates the number of additional layers and base composite percentages on the front of each of the four turnout coats evaluated.

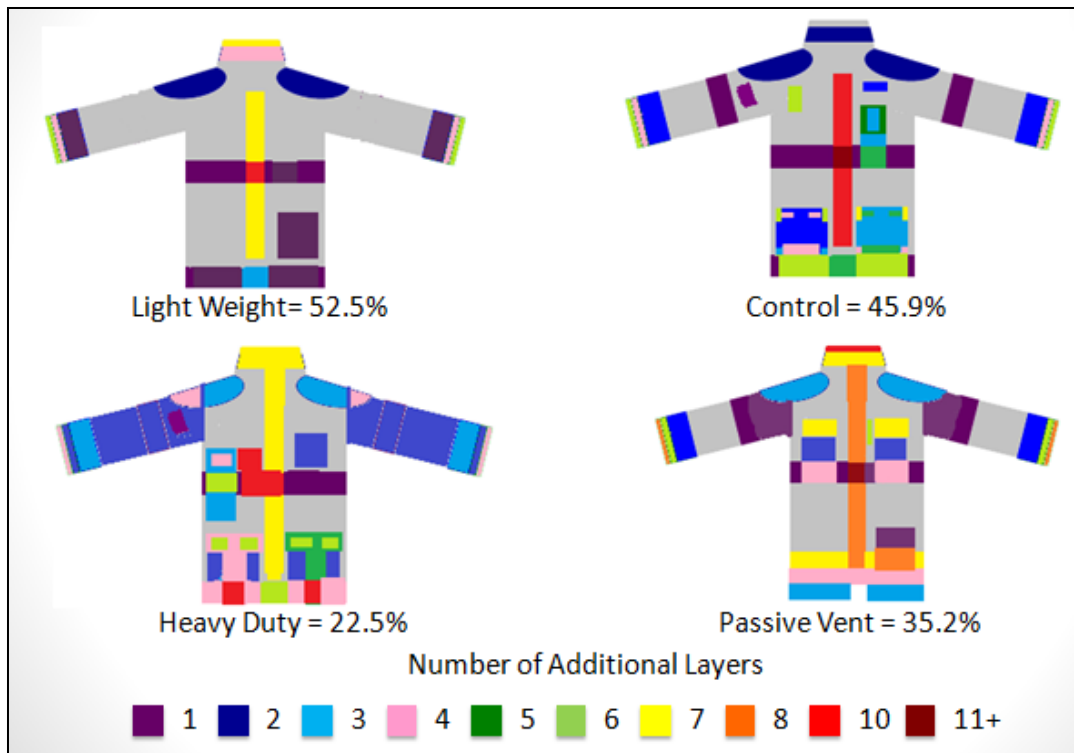


Figure 5-3. Base composite percentage and additional layer analysis of turnouts.

The front of the coat is where a large amount of accessories and reinforcements are placed between front pockets, hooks, loops, radio pockets, patches, trim, and the front zipper closure. Figure 5-3 illustrates the large difference in additional layers among the fronts of each coat evaluated. The light weight and control suits have closer to 50% base composite area while the heavy duty suit has just 22% base composite area with the foam composites placed all along the sleeves and chest areas. For the purposes of this study, bulk has been defined by both the number of layers in a turnout, as well as by the thickness of those layers. The first measurement of additional layers and base composite percentages demonstrates the bulkiness of the heavy duty and passive vent suits compared to the standard control turnout.

The lightweight suit reflects a reduction of bulk beyond what is typically found on the market in a control suit.

5.3.2 Fabric Level TPP and THL

To further determine the impact of these additional layers, fabric level tests for thermal protection and heat loss were conducted. Ten areas were tested including the coat and pant overlap, the addition of pockets, the boot and pant overlap, labels, trim, and reinforcements in the shoulder and knee areas. Figure 5-4 illustrates both the TPP and THL results of each area on the bench level.

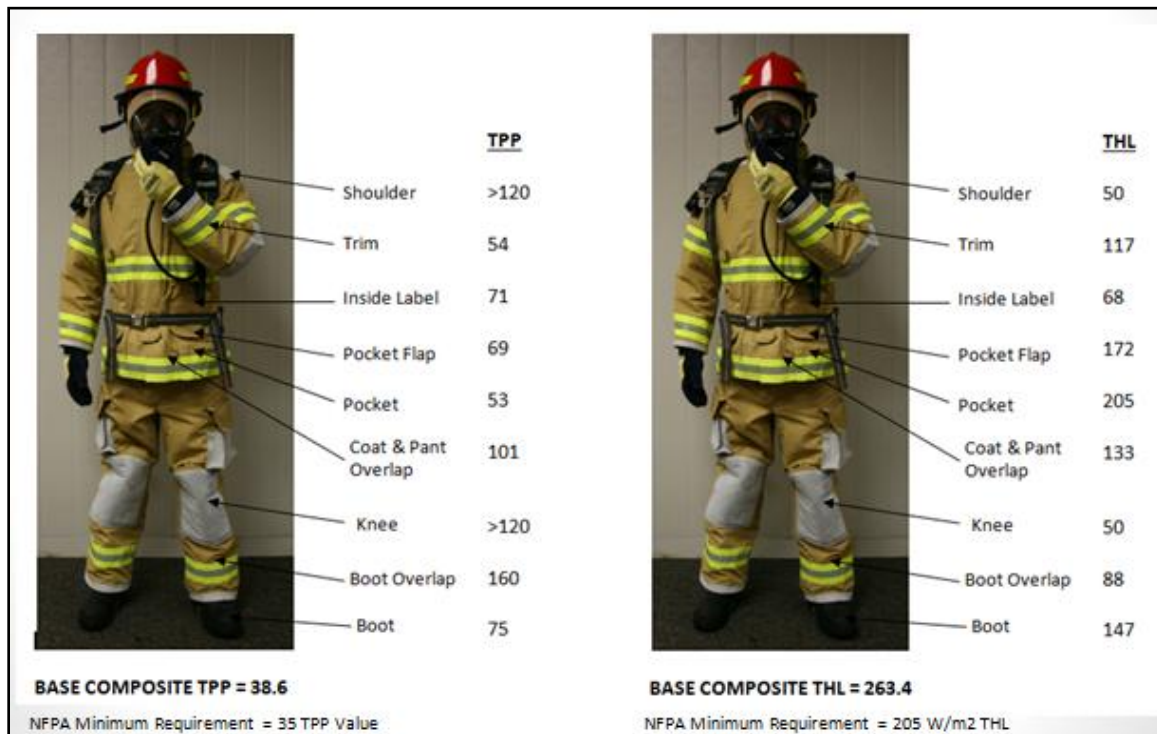


Figure 5-4. Fabric level TPP and THL results of structural firefighter garment components.

Fabric level TPP results demonstrate a sharp increase in thermal protection, far above and beyond the required 35 TPP rating specified by the NFPA. The base composite alone had a TPP rating of 38.5 cal/cm². Just by adding an additional outer shell layer as a pocket, the TPP rating in that area is increased to over 50 cal/cm². Add another outer shell layer for a pocket flap and the TPP value increases to almost 70 cal/cm². When constructed into a garment, there is often a large overlap between the coat and pants in the middle torso region. The TPP value measured where this overlap occurs is over 100 cal/cm², far more than the firefighter needs for adequate protection. The addition of trim and a label create TPP ratings exceeding 54 and 75 cal/cm², respectively. The largest TPP values were measured in the shoulder, knee, and boot overlap areas, well above 120 to 160 cal/cm². These results demonstrate the need to reduce bulk by decreasing the number of additional layers in the turnout composite. Figure 5-5 shows the individual garment component TPP results in comparison to the minimum NFPA 1971, 35 cal/cm² requirement.

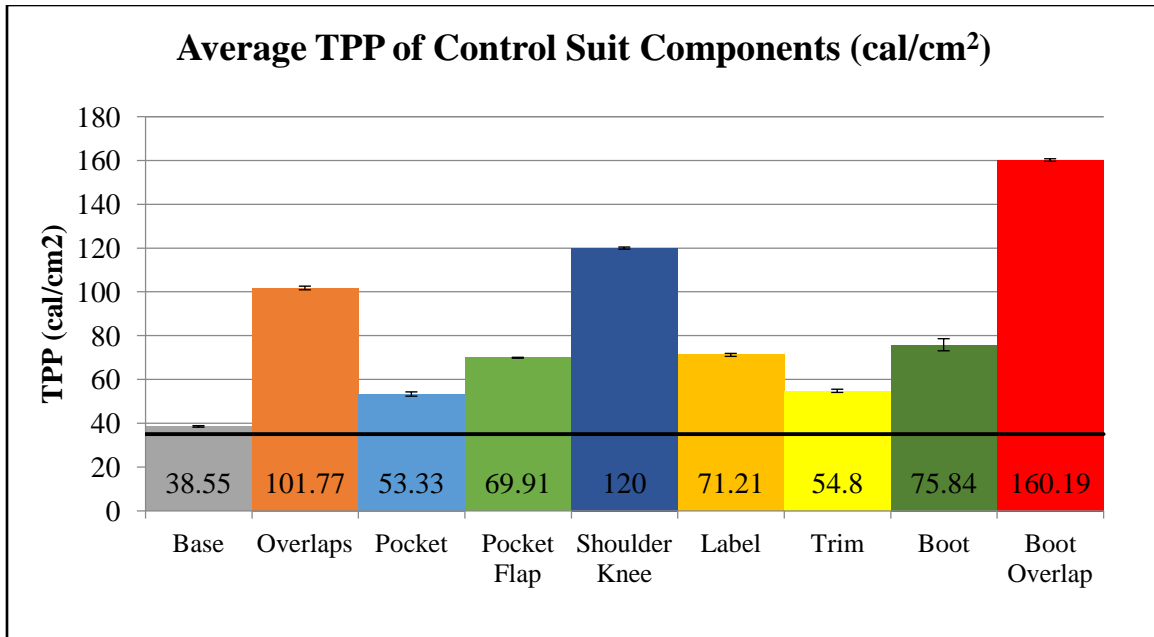


Figure 5-5. Average TPP values of control suit garment components on the fabric level.

Bench level THL results examined the effect of increased thermal protection on breathability and heat loss in specific areas of the garment. NFPA 1971 requires a fabric level THL value of at least 205 W/m². Of the ten garment components tested, only one passed the NFPA requirement for heat loss. The base composite plus one layer of outer shell, to demonstrate the effect of a pocket being added, resulted in a THL of exactly 205 W/m², the absolute lowest value considered to pass. The addition of just one outer shell layer resulted in a 58 W/m² decrease in THL, compared to the base composite, which is significant enough to be felt by the wearer (Calfee, 2013). Figure 5-6 demonstrates the THL results on the fabric level of each garment component tested.

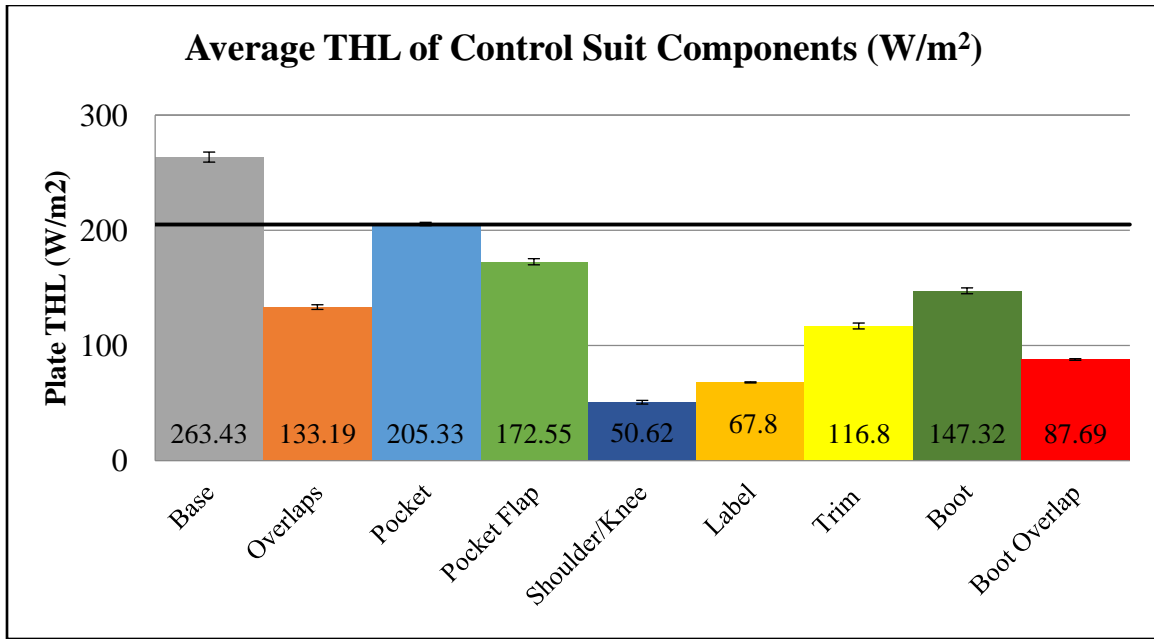


Figure 5-6. Average THL values of control suit garment components on the fabric level.

The largest reduction in heat loss was measured in the shoulder and knee reinforcement areas with a THL value of only 50.6 W/m². All garment components tested, except for the addition of a single outer shell layer, failed to meet the minimum NFPA requirement for THL.

The TPP and THL fabric level results of additional layers illustrate the detrimental effect of bulk when added to structural firefighter turnouts. Thermal protection is greatly exaggerated above the 35 cal/cm² required rating for TPP with the addition of fabric layers for pockets, knee and shoulder padding, and garment overlaps. This results in drastically reduced breathability in these corresponding areas, especially for the shoulders and knees. A

strategic reduction in bulk from either the inside, outside, or both, of the garment is necessary to reduce the areas of overprotection and improve heat loss.

The second measurement for defining bulk was the thickness of the additional layers. The thickness of each garment component tested on the fabric level was measured and correlated with the TPP and THL results. Figures 5-7 and 5-8 illustrate these correlations.

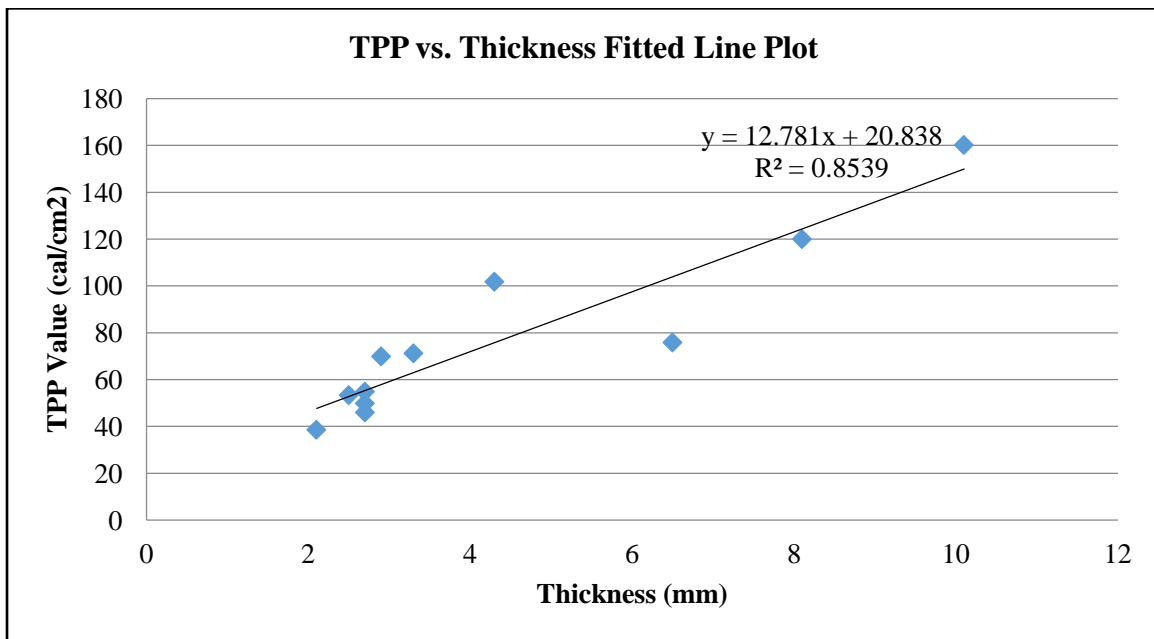


Figure 5-7. Correlation between TPP and fabric thickness of garment components.

There was a strong, positive correlation ($r^2=0.85$) established between thickness and thermal protection. As the thickness of the fabrics and layers increased, so did the thermal protection. Therefore, the TPP of a base composite is strongly related to the thickness of the fabric and air layers in the clothing system.

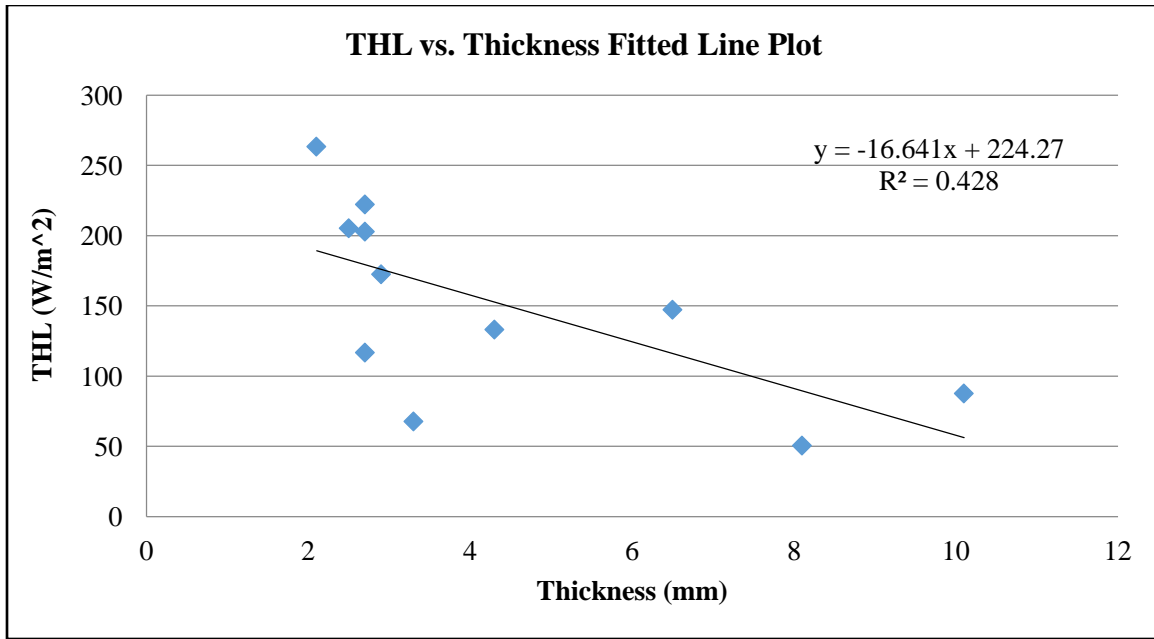


Figure 5-8. Correlation between THL and fabric thickness of garment components.

A strong correlation ($r^2=0.43$) was not established between hot plate THL and fabric thickness. The regression line does not represent the data well. These results indicate thickness is not a good indicator of the THL of a fabric composite. This is most likely due to other factors which affect THL, including the number of clothing layers and air gaps, air permeability of the fabric, and type of material.

5.3.3 Garment Level THL

A final evaluation for heat loss was conducted on the garment level using a sweating thermal manikin. Thermal and evaporative resistance measurements were taken in a static condition with the manikin standing still and under still air conditions (0.4 m/s wind speed). Figure 5-9 illustrates the differences in THL between the four suits with varying levels of

bulk. There was no statistically significant difference in THL, on the garment level, between the standard control turnout and the lightweight suit. This demonstrates that at a certain point, a reduction in bulk on the garment's surface area will no longer provide additional benefits for heat loss. Between the control and heavy duty suits there was a 10.9 W/m² increase in THL caused by the addition of bulk. Differences in THL between the control and heavy duty ($p < 0.01$), control and passive vent ($p < 0.1$), and heavy duty and passive vent ($p < 0.01$) were all statistically significant at the 90% confidence level or higher.

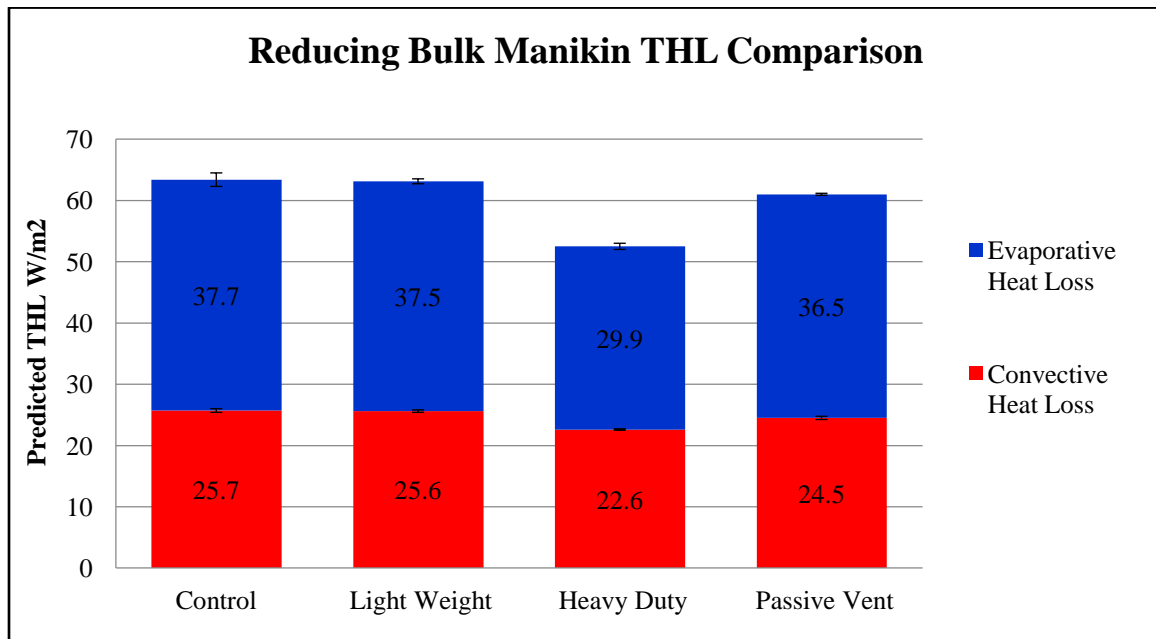


Figure 5-9. Manikin THL results of firefighter turnouts with varying levels of bulk.

Figure 5-9 illustrates the overall THL results for each suit according to their convective and evaporative heat loss. All four suits have similar heat loss values except for

the heavy duty suit which has a slightly lower convective heat loss (22.6 W/m^2) and an even lower evaporative heat loss (29.9 W/m^2). The passive vent had a higher level of bulk than the control but not as much as the heavy duty suit. The passive vent had more layers in the upper chest, back, and shoulders but their thickness was much less than the single foam layer in the heavy duty suit. These results indicate that thickness and type of material may contribute more to heat stress than the number of layers. Both should be considered, however, when evaluating how to reduce bulk in protective clothing for improved breathability and heat loss.

5.3.4 Virtual Modeling

To determine how clothing bulk impacts physiological comfort, the thermal insulation and evaporative resistance data from the predicted manikin THL testing was modeled. The control, light weight, heavy duty, and passive vent suit data was modeled according to the protocol described in Chapter 4, section 4.3.2. Figure 4-10 demonstrates the predicted core body temperature for each suit in a vehicle extrication scenario, with a full structural ensemble, including SCBA, worn on the sweating thermal manikin.

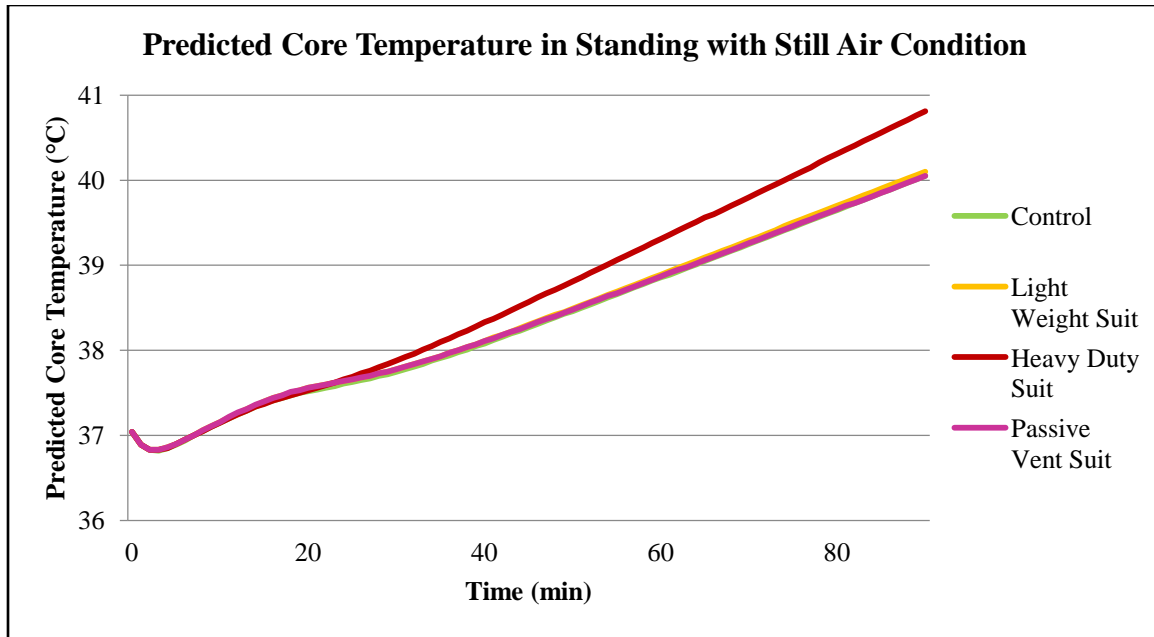


Figure 5-10. The predicted average core body temperature for each suit in a standing with still air test condition.

Predicted core body temperature illustrates the detrimental effects of additional clothing insulation on the physiological comfort of the wearer. By the end of the 90 minute protocol, all four suits resulted in potentially fatal predicted core body temperatures greater than 40°. The control, light weight, and passive vent suits had predicted core temperatures between 40.05°C to 40.1°C, while the heavy duty suit, with significant increases in clothing thickness, had a predicted core temperature of 40.8°C. This 0.7°C increase in predicted core temperature when wearing the heavy duty suit demonstrates its negative impact on wearer comfort.

Figure 5-11 shows the correlation between the maximum predicted rise in core temperature throughout the protocol and the overall average THL measured on the sweating

thermal manikin in the standing with still air condition. These results demonstrate a strong correlation ($R^2 = 0.94$) between the predicted rise in core body temperature and the manikin THL values. In the natural convection (standing with still air) condition, the reduction in heat loss of 10.9 W/m^2 for the heavy duty suit led to a 0.7°C predicted increase in core temperature.

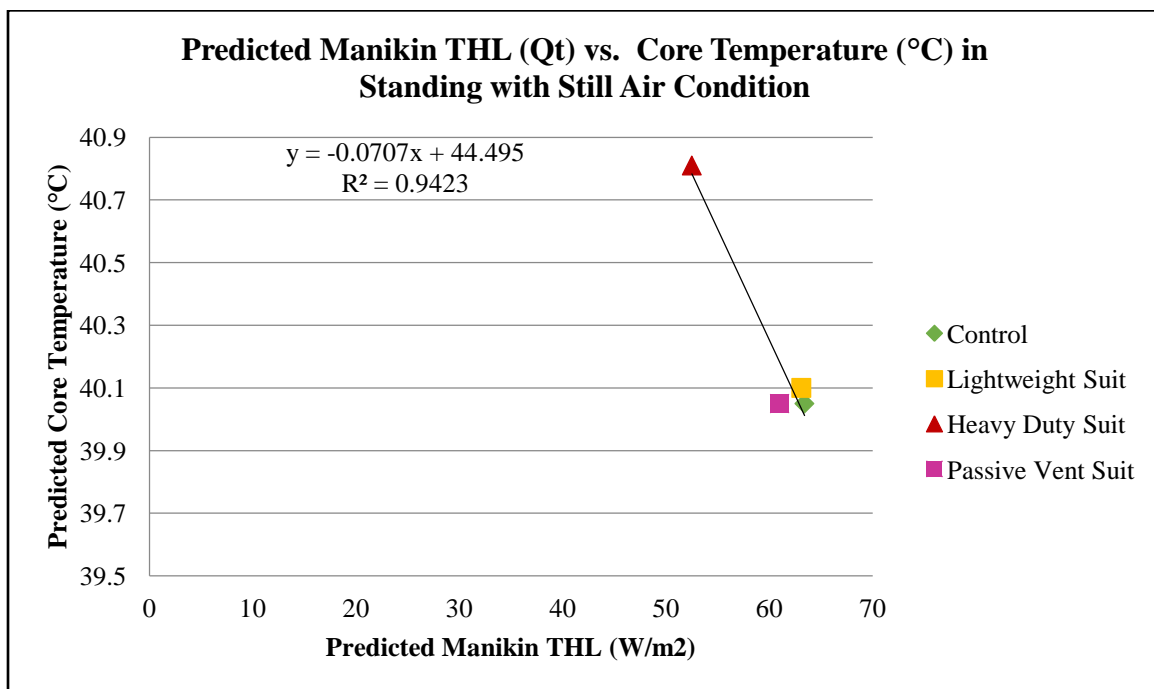


Figure 5-11. Correlation between the predicted maximum rise in core temperature and the overall average THL for each suit in the standing with wind condition.

The predicted skin temperature and predicted sweat rate were also modeled for each suit in the bulk analysis. Skin temperature differences between the control, light weight, and passive vent suits were negligible ($39.57\text{-}39.64$). However, the heavy duty suit led to an

almost 1°C (0.94°C) increase in predicted skin temperature. Sweat rates for all four suits reached the maximum 30 g/min before the end of the 90 minute protocol. The heavy duty suit, however, reached the predicted sweat rate maximum earlier than any of the other suits, at 51 minutes in the protocol, compared to the control suit, which reached the maximum at 59 minutes. Charts illustrating the predicted skin temperature and predicted sweat rate of each suit over the 90 minute modeling protocol can be found in Appendix C.

5.4 Discussion and Conclusion

The reduction of bulk data indicates the harmful impact on wearer heat stress when adding additional layers and thickness into the garment design. The turnout coat and pants contribute a significant amount of weight to the firefighter's overall ensemble. By taking reinforcements and extra layers into consideration, it is evident that current fabric level TPP and THL standards do not capture the full picture of how physiological comfort is effected by extra bulk. Lower levels of bulk in the passive vent, control, and light weight suits led to greater heat loss, lower core and skin temperatures, and a reduced time before maximum sweat rate was reached. The additional layers and increased thickness from the foam composites and additional reinforcements in the heavy duty suit demonstrated a detrimental impact on clothing comfort, based upon the predicted physiological responses.

These findings will be utilized when designing prototypes for human wear trial evaluations in order to better inform the down selection stage of the functional design and product development process. Future research in this area should consider the incorporation of base layers as part of the turnout ensemble, as stationwear currently worn underneath the turnout is not factored into the measurements of protection and breathability of the clothing

system. An overall reduction in layers may be achieved if the base layers that firefighters currently wear were considered a part of their thermal protection. In turn, layers from the current turnout ensemble may be reduced, imparting greater potential for heat loss to occur. This specific clothing modification will be further investigated in the next chapter as a systems level modular approach for specified working conditions.

*The author would like to note that portions of the research presented in this chapter were published in the trade magazine, "Fire Engineering" (McQuerry, Barker, Hummel, & Deaton, 2015).

6 Modular Layering Approach for Heat Loss Improvement in Structural Firefighter Protective Clothing Systems

6.1 Introduction

Heat stress is a leading cause of firefighter fatalities (Rossi, 2005). The potential for heat loss through turnout gear is a significant factor in considering firefighter heat stress. When multiple clothing layers are worn together, as in structural firefighter turnouts, the increased metabolic load on the body when performing physical activity will reduce the time to fatigue and exacerbate problems of heat dissipation (Duggan, 1988). Structural firefighter turnouts are designed to protect against the worst case flashover condition in a structural fire exposure. However, working conditions where the risk of fire and flame exposure are present account for only 10 to 20% of all activities firefighters perform (Rossi, 2005). Up to 99% of a firefighter's time may be spent completing normal working tasks in which the threat of heat and flame is nonexistent (Den Hartog, 2010). These normal working tasks include responding to goodwill calls, motor vehicle accidents, performing vehicle extrications, and conducting search and rescue operations (FireRescueOne, 2014).

Under these normal working conditions, extreme heat and flame exposure do not pose a threat, however, in the US the full three layer turnout is required to be worn in all scenarios according to NFPA 1971 (NFPA, 2013). Therefore, firefighters need lighter weight and less restrictive turnouts for specific applications in order to prevent excessive metabolic heat production which leads to heat stress (Ciampo, 1998). While some suits, such as an USAR (Urban Search and Rescue) exist on the market today, the majority of departments, especially volunteer firefighters, cannot afford to purchase multiple suits for specific operations. By

redesigning the current turnout into a modular system, heat stress may be reduced without creating an additional economic burden. Further research should be done to determine each layer's impact on thermal insulation, evaporative resistance and overall heat loss on the garment level. This experiment explored individual and multi-layer garment arrangements for specific working conditions, such as USAR and vehicle extrication, in order to reduce the heat stress that additional clothing insulation causes between 80 to 90% of a firefighter's working time.

6.2 Experimental Methodology

6.2.1 Materials

In total, seven different layer configurations were evaluated including three single layer garments, two double layer, and two triple layer arrangements. The traditional three layer arrangement of the outer shell (OS) + moisture barrier (MB) + thermal liner (TL) was used as the standard control to compare heat loss improvements. Each individual layer of the three layer base composite, the outer shell (OS), moisture barrier (MB) and thermal liner (TL), was tested individually as a separate garment. Two double layer configurations were tested by removing either the moisture barrier (OS+TL) or thermal liner (OS+MB). Besides the traditional three layer arrangement (OS+MB+TL), a second triple layer arrangement was tested by rearranging the moisture barrier and thermal liner layers (OS+TL+MB). Table 6-1 describes each of the seven layering configurations that were tested. All garments were tested assuming an extrication or motor vehicle accident call scenario. Instead of wearing the full ensemble, the thermal sweating manikin was dressed in a pair of trousers, coat, boots, gloves, and helmet.

Table 6-1. Configuration of modular approach garment layers.

Composite Layers	Configuration Label	Number of Layers
Outer Shell	OS	1
Moisture Barrier	MB	1
Thermal Liner	TL	1
Outer Shell+Moisture Barrier	OS+MB	2
Outer Shell+Thermal Liner	OS+TL	2
Outer Shell+Moisture Barrier+Thermal Liner	OS+MB+TL	3
Outer Shell+Thermal Liner+Moisture Barrier	OS+TL+MB	3

6.2.2 Procedures

Testing to evaluate the heat loss capability of each configuration was completed using a Newton Sweating Thermal Manikin (Thermetrics, Seattle, USA). The Newton 34 zone model includes separately controlled heated sections with built-in pores for sweating and a fluid pre-heater inside the manikin to ensure the "sweat" coming through the pores is maintained at the proper temperature. The modular approach garment configurations were evaluated in static and dynamic conditions as shown in Table 6-2.

Table 6-2. Sweating thermal manikin test conditions.

Condition	Air Speed	Movement
Static	0.4 m/sec	Standing
Dynamic	2 m/sec	Walking

Testing in the static condition with still air and a standing manikin assesses the natural convection of the suit without the addition of body movement or wind which both significantly increase heat loss (Ingvar Holmér, 2006). In the dynamic condition, body movement was introduced by making the manikin walk which demonstrated the effect of pumping. In addition, wind was added at two meters per second to evaluate forced convection through air movement. For specific details on the sweating thermal manikin THL test methodology, please see Chapter 3, section 3.2.2.

To further analyze whether differences in predicted manikin THL make a meaningful impact on physiological comfort, human thermal modeling was conducted. The OS, OS+MB, OS+TL, OS+MB+TL, and OS+TL+MB configurations were modeled according to the protocol and methodology described in Chapter 4, section 4.3.2.

6.2.3 Statistical Analysis

The sample size for each of the seven suit configurations was three (three wet reps and three dry reps were used to calculate an average overall THL). To determine the statistical significance of the measured differences in predicted manikin THL, a one-way ANOVA, was conducted to determine if significant differences were present between groups. If differences were identified ($p < 0.05$) between the results, independent t-tests were carried out to determine which groups were significantly different from one another. Two-sample t-tests, which assume equal variances between the two groups measured, also assume the data is normally distributed. All data was tested for normalcy to ensure two-sample t-tests could be properly conducted on the data set. Normal distributions were confirmed through a probability plot and the Anderson-Darling test statistic using Minitab statistical analysis

software. The variance ratio F-test was conducted to confirm equal variances between groups. An F-value less than F-Critical one-tail indicates the variances are equal. A p-value less than 0.05 indicates a significant difference in THL between the configurations.

Statistical significance for virtual heat strain modeling was determined by analyzing if each data point fell within two standard deviations of the sample mean. This method of determining statistical significance was limited by the lack of repeated measures inherent to the modeling and ventilation estimation methodologies.

6.3 Results

6.3.1 Thermal and Evaporative Resistance of Base Composite Layers

Manikin THL results for the three individual composite layer garments (outer shell, moisture barrier, thermal liner) are shown in Figure 6-1. In the static condition, statistically significant differences in manikin THL were found between all three layers ($p < 0.05$). Heat loss was much higher in the dynamic test condition which was to be expected as the addition of wind and body movement greatly increase heat loss (Ingvar Holmér, 2006). Differences in manikin heat loss between the individual layers were not as prominent in the dynamic condition. The thermal liner layer had the highest manikin THL values in both test conditions.

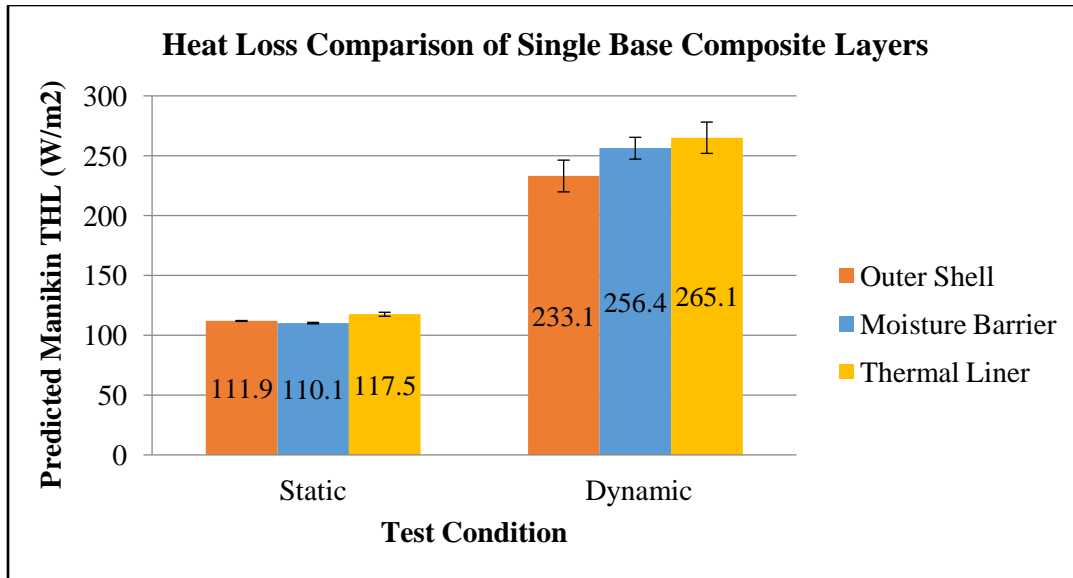


Figure 6-1. Manikin THL results of each base composite layer tested in both the static and dynamic conditions. Error bars represent standard deviation.

Thermal resistance (insulation) and evaporative resistance measurements between the three layers in each condition were also compared. There was no statistical difference in thermal insulation between the three base composite layers in the static condition. The thermal insulation values did show significant differences in the dynamic condition. The evaporative resistance of each layer was statistically different from one another in the static condition. The only difference in the evaporative resistance of the layers in the dynamic test condition was between the outer shell and thermal liner. Table 6-3 below gives the thermal and evaporative resistance measurements, in both test conditions, for the three individual layers, two double layers, and two triple layer arrangements. The standard deviation is given in parentheses.

Table 6-3. Thermal and evaporative resistance measurements of individual base composite layer suits in static and dynamic conditions on a sweating thermal manikin.

Base Composite Layer	Thermal Resistance (I_{tot})		Evaporative Resistance ($I_{e,tot}$)	
	Static	Dynamic	Static	Dynamic
Outer Shell	0.250 (0.010)	0.141 (0.000)	0.050 (0.000)	0.022 (0.002)
Moisture Barrier	0.234 (0.001)	0.121 (0.001)	0.053 (0.001)	0.021 (0.001)
Thermal Liner	0.263 (0.001)	0.138 (0.001)	0.045 (0.001)	0.019 (0.001)
OS + MB	0.300 (0.003)	0.157 (0.001)	0.065 (0.000)	0.028 (0.001)
OS + TL	0.341 (0.003)	0.196 (0.002)	0.063 (0.000)	0.025 (0.002)
OS+MB+TL	0.346 (0.000)	0.197 (0.001)	0.073 (0.003)	0.029 (0.002)
OS+TL+MB	0.362 (0.003)	0.207 (0.003)	0.079 (0.002)	0.031 (0.002)

The results above were further confirmed by the dry and wet heat loss values of each layer. The moisture barrier had the highest dry heat loss, reflecting its low thermal resistance properties, and the lowest wet heat loss, demonstrating its high evaporative resistance properties. The same is true for the thermal liner which had the highest wet heat loss, reflecting a low evaporative resistance value, and the lowest dry heat loss, depicting its high thermal insulation value. Figure 6-2 below illustrates the dry and wet heat loss values for each individual layer in the static testing condition.

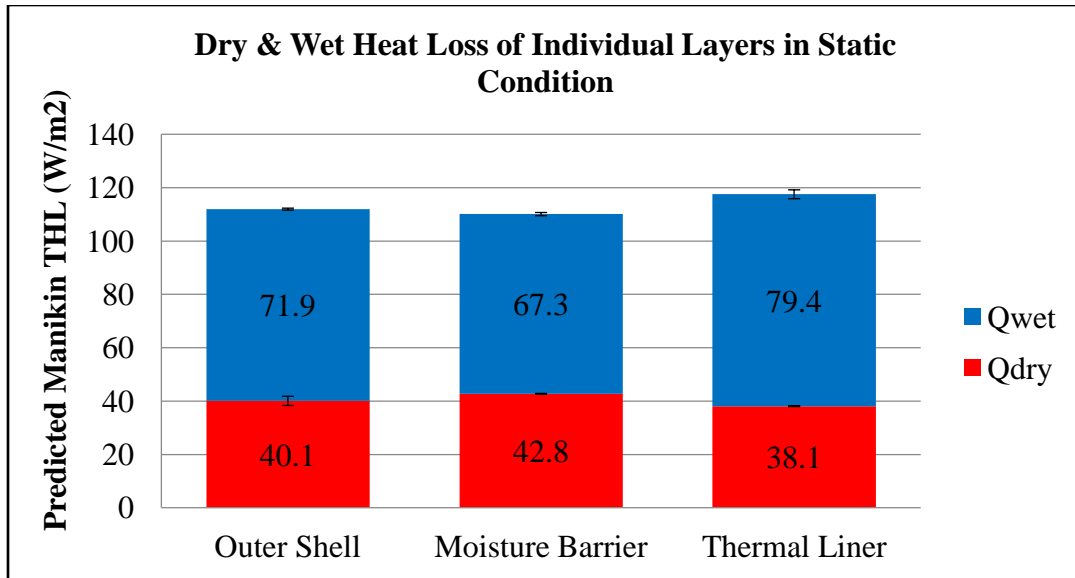


Figure 6-2. Dry and wet heat loss results of each base composite garment tested in the static condition. Error bars represent standard deviation.

6.3.2 Double Layer Composite Manikin THL

In the static test condition, which evaluates natural convection, there was little difference between the two double-layer systems. The OS+MB and OS+TL systems were similar in THL at 88.6 W/m² and 86.4 W/m², respectively. This small difference in manikin THL, however, was found to be statistically significant ($p < 0.05$). In the dynamic condition, the small difference between these two systems was not significant. These results indicated there were no practical significant differences between the two layer systems, regardless of fabric layer combinations. Figure 6-3 below illustrates the differences in manikin THL between the two double layer arrangements in both test conditions.

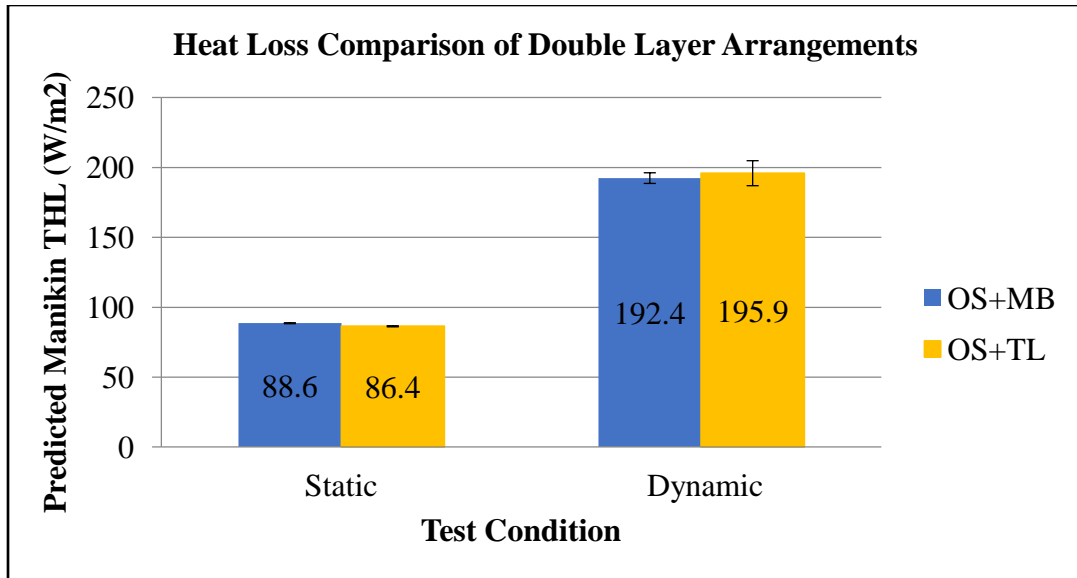


Figure 6-3. Manikin THL of double layer garments tested in both the static and dynamic conditions. Error bars represent standard deviation.

6.3.3 Triple Layer Composite Arrangements Manikin THL

Differences between the two triple layer arrangements were more pronounced. The traditional three layer base composite is arranged as the OS+MB+TL. A nontraditional rearrangement was also evaluated with the moisture barrier against the skin and thermal liner in the middle (OS+TL+MB). In both test conditions, the nontraditional arrangement has lower heat loss values than the traditional Control. Figure 6-4 depicts manikin THL results of the triple layer arrangements in both test conditions.

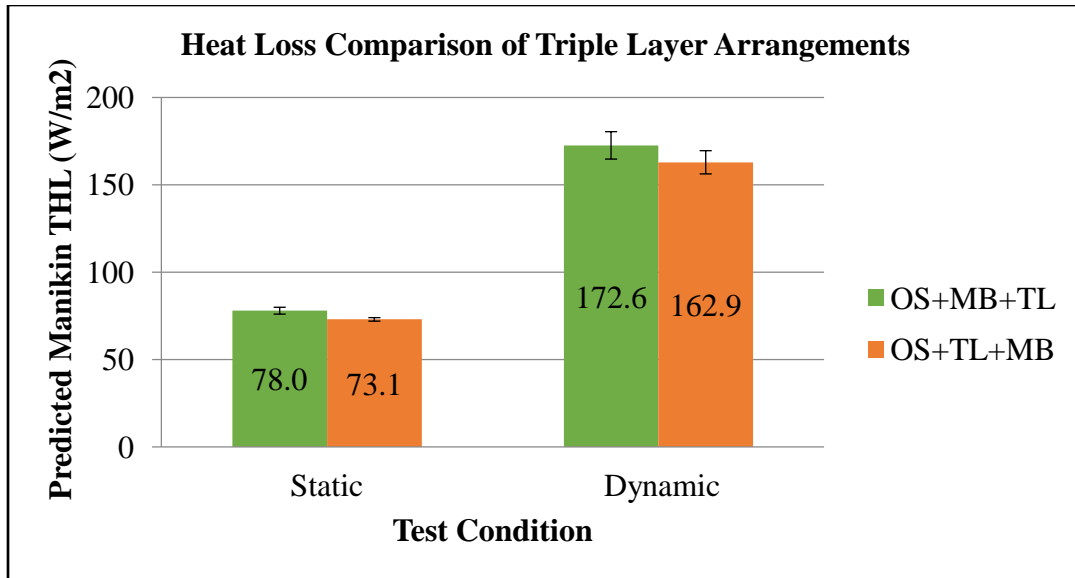


Figure 6-4. Manikin THL of each triple layer arrangement tested in both the static and dynamic conditions. Error bars represent standard deviation.

6.3.4 Comparison of Modular Approach System

A comparison of the manikin THL of each layered system is necessary to determine the efficacy of reducing the three layer base composite for specific working conditions. In the static condition, the manikin THL of a single outer shell layer was 111.9 W/m^2 which is significantly greater ($p < 0.05$) than the two layer systems. This single layer outer shell system could be worn by the firefighter when conducting USAR activities. USAR suits are specialized garments deployed in non-structural firefighting situations for multiple task use including confined space operations and road traffic accidents (Fire Product Search, 2015) . For these purposes, the outer shell layer of the turnout should be sufficient for providing the necessary levels of protection.

The two layer systems had an average manikin THL of 87.5 W/m² which is significantly greater ($p < 0.05$) than the traditional three layer composite system. The same results are evident in the dynamic testing condition when pumping and wind are present. The OS+MB configuration would be worn as a vehicle extrication garment, or for other working conditions where liquid or chemical protection is necessary but thermal protection is not. Figure 6-5 illustrates the advantages of reducing the three layer turnout to a double or single layer construction for specific working conditions by showing the significant improvement ($p < 0.05$) in heat loss gained with the removal of each additional layer.

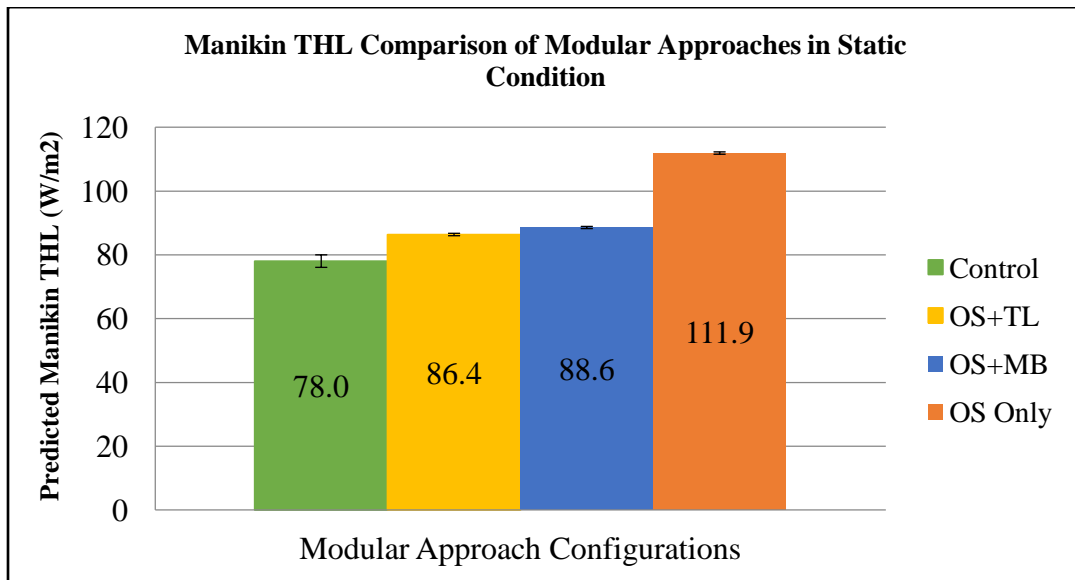


Figure 6-5. Total Heat Loss comparison of single, double, and triple layer turnout garments tested in the static condition. Error bars represent standard deviation.

6.3.5 Virtual Modeling

The single layer OS, two double layer, and two triple layer configurations were modeled for predicted physiological responses according to the protocol used throughout this study, highlighted in section 4.3.2. The raw thermal insulation and evaporative resistance data from both test conditions (static and dynamic) were modeled in the same protocol. Figure 6-6 highlights the predicted core body temperature of each modular system in the static (standing with still air) condition.

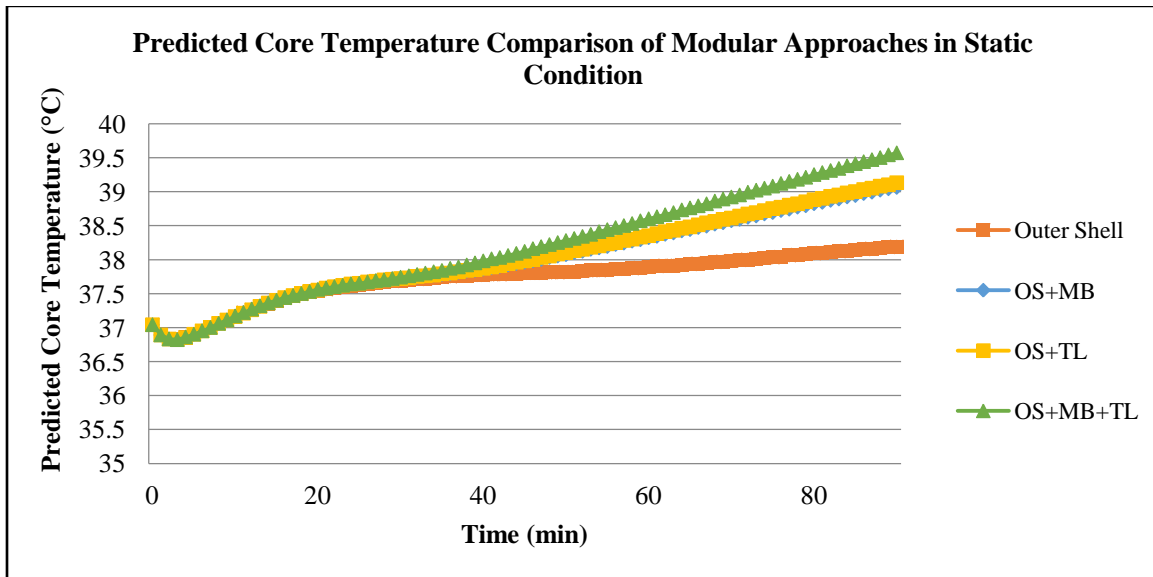


Figure 6-6. Predicted average core body temperature for each modular suit configuration in a standing with still air test condition.

The predicted core temperature for each modular approach configuration shows the improvement in physiological comfort as layers are removed from the clothing system. A 10

W/m² improvement in manikin THL from the three layer to a two layer system, corresponded to a predicted core temperature reduction of 0.5°C, in the standing with still air condition. By reducing the system from the three layer control to a single layer outer shell for USAR applications, heat loss was increased by 34 W/m² and predicted core temperature was reduced by 1.4°C. Due to the very narrow range in which core temperature can fluctuate before symptoms of heat illness or fatality occur, a drop in core temperature greater than one degree Celsius should be significant and meaningful for the wearer's comfort. Further human wear trial evaluations are necessary to confirm this measured difference in core temperature.

Predicted skin temperature and predicted sweat rate results in the static condition followed similar trends to the predicted core temperature results. There was a 0.67°C drop in predicted skin temperature when the thermal liner layer was removed and a 2.07°C decrease when the system was reduced to a single outer shell layer. The three layer control turnout and both double layer configurations reached a predicted maximum sweat rate of 30 g/min in the static condition. The single layer OS, however, only reached a predicted sweat rate of 18.9 g/min in the same test condition after the 90 minute protocol.

In the dynamic condition, differences in predicted core temperature between suits were less pronounced. Forced convection through wind and walking will increase the heat loss through all clothing systems, reaching an upper limit. The same trends between suits were identified with the single and double layer configurations having lower predicted core temperatures than the three layer control turnout. However, the largest measured difference was only 0.13°C, between the control and single layer OS system.

Differences in predicted skin temperature and predicted sweat rates, however, were more pronounced in the dynamic test condition. Removing the thermal liner led to a 0.92°C drop in predicted skin temperature, whereas, removing both inner liner layers corresponded to a 1.3°C reduction. Predicted sweat rate results also demonstrated the benefits of a modular system for specific working conditions. The predicted sweat rate of the control turnout (OS+MB+TL) was 10.6 g/min, modeled in the dynamic condition, compared to the OS+TL, OS+MB, and OS only at 9.36, 8.15, and 6.6 g/min, respectively. Figures 6-7 and 6-8 illustrate these results. Graphs illustrating the predicted core temperature in the dynamic condition and the predicted skin temperature and predicted sweat rate in the static test condition can be found in Appendix D.

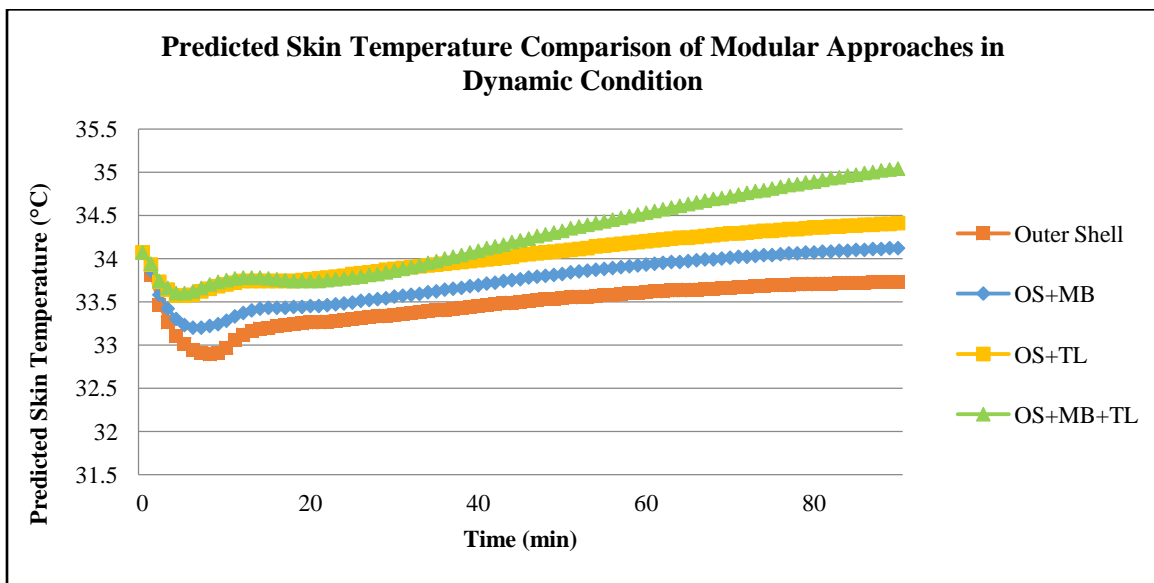


Figure 6-7. The predicted average skin temperature for each suit using walking with wind test condition data in the physiological model.

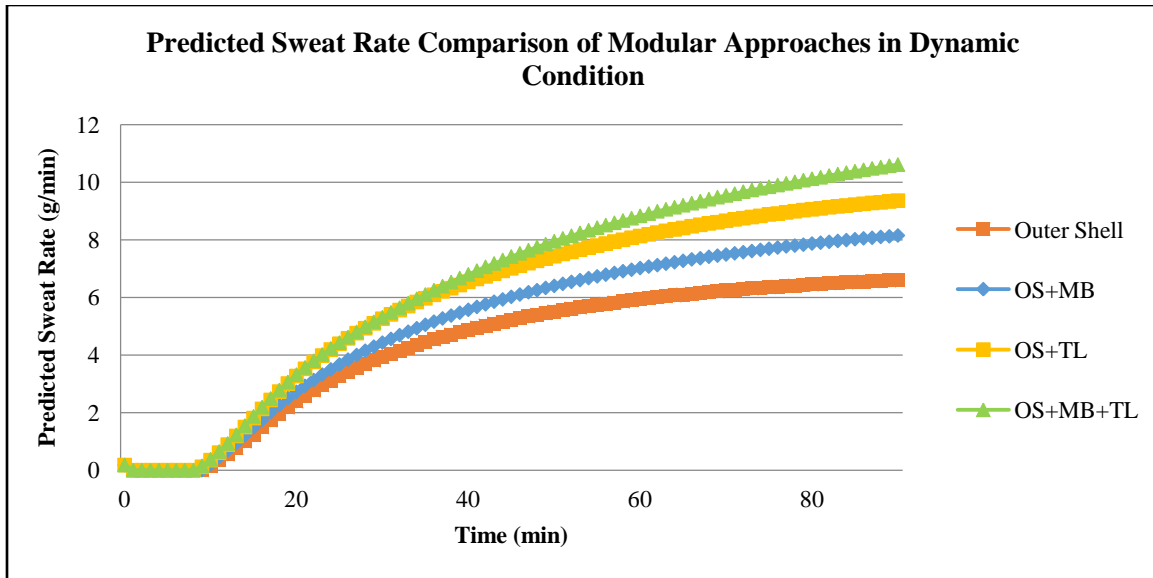


Figure 6-8. The predicted average sweat rate for each suit using walking with wind test condition data in the physiological model.

6.4 Discussion

The results of each modular approach, in both static and dynamic conditions, are discussed below. Single and double layer suits showed statistically significant improvements in heat loss compared to the traditional three layer arrangement. The individual single layer suits are compared to one another along with the double and triple layer arrangements.

It was hypothesized that the moisture barrier layer would have the lowest thermal insulation and highest evaporative resistance of the three layers because of its construction and liquid impermeable properties. In both the static and dynamic ($p < 0.05$) conditions the moisture barrier had the lower thermal resistance. The moisture barrier also had the highest evaporative resistance in the static condition ($p < 0.05$). The thermal liner layer performs in an opposite manner with the highest thermal resistance and lowest evaporative resistance. In

both the static and dynamic conditions the thermal liner had the lowest evaporative resistance. The thermal resistance of the outer shell was slightly higher ($p < 0.05$) than the thermal liner in the dynamic condition only.

Findings show there are significant differences in thermal insulation, evaporative resistance, and overall heat loss between each of the base composite layers. Each layer has a significant impact on the overall clothing system and the wearer's physiological comfort. This is especially true in the dynamic test condition which includes both walking and wind. In the static condition, there were no significant differences in thermal insulation between layers indicating they all contribute similarly to the overall insulation of the three layer composite. Differences are noted in the dynamic condition when forced convection occurs. The thermal liner actually provided the greatest heat loss of the three layers, even though it is thicker (1.35mm) than the outer shell (0.44mm) and moisture barrier (0.36mm). This is most likely due to the thermal liner's higher air permeability (94.9 cfm) versus the outer shell (11.3 cfm) and moisture barrier (<0.56 cfm). Just as each layer provides its own unique form of protection for the wearer, its individual fabric and construction properties provide different contributions to overall heat loss, insulation, and resistance. To determine how the removal of each inner liner layer (moisture barrier and thermal liner) would impact heat loss in a modular turnout, further testing of double layer systems was conducted.

During some firefighting activities the need for thermal protection is not present or there is no need for liquid or chemical protection. In these conditions it may be possible to wear a two layer system which eliminates the unnecessary protection provided by an

additional layer. To determine if this concept would be effective for reducing heat strain, the heat loss of each two layer and three layer system was tested on a sweating thermal manikin. Results from the double-layer configurations indicated that either system would relieve heat at a similar level, regardless of whether the moisture barrier layer was worn for liquid protection, or the thermal liner layer was worn for thermal protection.

In working conditions, such as a structural fire, where the threat of heat and flame are present, the full triple-layer base composite must be worn. However, to the author's knowledge, no research has been conducted on the re-arrangement of the inner liner layers and its impact on heat loss. To determine if placing the moisture barrier closer to the skin would improve the transfer of heat and moisture to the external environment, this rearrangement was evaluated.

For the two triple layer configurations, in both the static and dynamic test conditions, the traditional arrangement (OS+MB+TL) had a higher manikin THL. This difference was statistically significant ($p < 0.05$) in the static condition only. These results indicate the traditional three layer base composite arrangement is more ideal for heat transfer compared to the rearrangement of the inner layers. Further research should include the evaluation of a tighter fitting moisture barrier which has been designed and manufactured specifically for this research study. While preliminary results did not show a benefit for placing the moisture barrier directly against the skin, a tighter fit may provide different results. Therefore, a tighter fitting moisture barrier, along with a tighter knit thermal liner material, should be evaluated as an analysis of air gap volume reduction (Chapter 7).

For the overall modular layering approach, an improvement in heat loss of 10 W/m^2 when removing a single layer, and 34 W/m^2 when removing both inner layers, indicates that a reduction in layers of the firefighter clothing system will significantly improve the heat loss of the ensemble. This is especially true when there is no liquid or chemical threat present and the outer shell layer may be worn alone. By designing a modular turnout system which provides all three capabilities (OS, OS+MB, and OS+MB+TL) in one garment, the risk of heat illness should be reduced for the firefighter. This type of modularity in a structural turnout garment would allow the firefighter to customize his or her clothing to the specific task at hand.

Interestingly, the data on the two layer systems show an approximately 20% decrease in THL, corresponding to a similar 20% increase in overall insulation, when any layer is added to the 1-layer system (cf. Figures 4-1 and 4-2). This is because the added clothing layer does not add its full insulation to the system (additive model), but rather the second layer fills the microclimate air layer underneath the outer layer. This reduces the overall effective air layers and enhances overall insulation compared to one clothing layer only, even if the distance between skin and outer clothing layer stays the same. Furthermore, with an additional third clothing layer (Figure 4-3), the air layers are further broken up, but this only leads to a further increase in insulation of about 10%. The additive heat loss effect due to motion and wind (dynamic condition) is smaller in the three layer systems in terms of absolute heat loss.

As these clothing systems typically consist of outer layers that have an “oversized” design, characterized by larger size microclimate air layer thicknesses, the differences

between the different clothing layers seem small. The existence of any clothing layer seems more important than the specific properties of these clothing layers as can be seen from the very small differences between the tests on different clothing layers and configurations. Significant reduction of overall insulation values, more than found in this study by simply removing one layer, would have to come from major decreases in microclimate thickness instead of changing fabrics. However, various studies have also shown that each addition of clothing layer leads to significant increases in effort and work load, and corresponding increases in metabolic heat production, as well as significant reductions in ergonomics and usability. Those factors may prove to be more important in acceptability and use of firefighter clothing with reduced layers. Currently, with the classic three layer system, clothing design has to be larger to allow for optimal motion. A reduction in clothing layers will allow for and favor a more 'sleek' clothing design, with smaller air layers, thus further improving overall ergonomics and physiological strain aspects.

An additional benefit to achieving modularity in a single turnout is its cost effectiveness. Fire departments are often limited in funding, especially rural, volunteer departments. By creating three specialized suits for the price of one, firefighters will be able to wear appropriate gear for every working condition. The resulting increase in heat loss should improve the physiological comfort experienced by the firefighter by reducing the onset of heat strain in specific working conditions. Further research needs to be conducted to confirm this prediction through human wear trial experiments.

Results demonstrate a reduction of layers in the traditional three layer structural firefighter turnout significantly improves heat loss through the clothing system. By reducing

the base composite from three layers to two, an increase in manikin THL of 10 W/m^2 was measured. Further reducing the system to a single, outer shell layer increases manikin THL by 34 W/m^2 (from 78 W/m^2 to 112 W/m^2). These statistically significant increases in heat loss may be practically significant for improving the physiological comfort of the firefighter.

Predictive human thermal modeling was used as an intermediary step to estimate the physiological responses in a realistic working condition. The results from human thermal modeling indicated a meaningful improvement in wearer comfort, especially for the single layer OS application for USAR activities. Reductions in core temperature and skin temperature, greater than 1°C , indicate practically significant improvements. Further testing on the human wear level is needed to confirm the predicted physiological responses.

6.5 Conclusions

The implementation of a modular firefighter turnout system is applicable for the majority of a firefighter's working conditions such as medical calls, search and rescue operations, and motor vehicle accidents. In these scenarios the need for thermal or liquid protection may not be necessary. When wearing the full three layer turnout in conditions where physical activity is performed, especially in warm environmental conditions, the risk of heat stress is increased. By reducing the turnout system to a double or single layer suit, in specified conditions, the resistance to heat loss is reduced. The caveat to this design strategy, however, is that by reducing clothing insulation, thermal, liquid, and chemical protection may be lowered, depending on which layer(s) are removed. It is important to note that each modular layering configuration should only be worn in the specified condition in which certain risks (i.e. heat, flame, chemicals) are not present.

Future research should be conducted on the human wear level to determine the actual measured physiological responses of a modular firefighter turnout garment. These garments should be tested in similar environmental and physical conditions as they would be worn. The core temperature, skin temperature, heart rate, and weight loss of each participant should be recorded and correlated to the predicted physiological responses and sweating manikin THL values.

As a caveat, it should be noted that this research describes the results of a limited laboratory study designed to provide a scientific basis for evaluating the effects of layering strategies in firefighter turnouts on heat loss. Care must be taken in drawing conclusions about the safety benefits from these data. The data describe the properties of selected fabrics in response to the controlled laboratory exposures and conditions that are specified. Study results must be weighed in light of the fact that no laboratory analysis can completely qualify complex firefighting events, which can be physically complicated and unqualified. This study was not intended to recommend or exclude any materials from any particular application. The adoption of a modular structural turnout into the fire service industry would require a change in training and firefighting tactics given reduced levels of protection with certain layering configurations. While some normal working conditions may not present an initial thermal or chemical threat, emergency situations are not always predictable. Therefore, further development of the modular system into an integrated prototype design would be necessary for specific firefighting operations.

*It should be noted that the above chapter has been accepted for publication in the Textile Research Journal (McQuerry, DenHartog, & Barker, 2016a).

7 Determination and Analysis of Air Gap Volume in Structural Firefighter Turnouts and its Relationship to THL

7.1 Introduction

The amount of heat and mass transferred through a clothing system is directly affected by the air gap thickness created between multiple clothing layers (Frackiewicz-Kaczmarek, Psikuta, Bueno, & Rossi, 2014). The air trapped between these layers, within the clothing microenvironment, contributes to the thermal insulation of the ensemble (G. Havenith, 2001). Air layers are inherent in clothing construction on the three-dimensional human form. They function, in addition to the clothing materials, to resist heat and moisture transfer between the skin and environment, hampering the amount of heat that may potentially be dissipated. Some literature, however, suggests that increased air gap thickness between eight to 13mm may in fact allow for more natural convection to take place, thus increasing heat and moisture exchange within the clothing system (Frackiewicz-Kaczmarek et al., 2014; Spencer-Smith, 1977).

For most clothing ensembles, the volume of air enclosed in the system's layers exceeds the volume of the fibers themselves, indicating clothing insulation is a function of material thickness, or the enclosed air layer (G. Havenith, 2001). Evaporative resistance of moisture through the garment is also heavily dependent on the thickness of the enclosed still air layers. This suggests that a reduction of air gap volume by using thinner, tighter fitting materials may lower the overall resistance to heat transfer. In that case, however, material components begin to play a more important role (G. Havenith, 2001). Material properties such as air permeability, along with coatings, membranes, and other treatments, directly

impact the evaporative resistance, as well. In structural firefighter turnouts the moisture barrier layer tends to play the biggest role in limiting evaporative heat loss due to its impermeability to air.

The study of air gap thickness and how it impacts heat transfer on the material level has been widely investigated. There have been limited studies, however, on how air gap volume affects heat and moisture exchange in real-life conditions with a full clothing ensemble. When considering actual garments, which are three-dimensional forms draped from flat fabric to fit a human silhouette (Frackiewicz-Kaczmarek et al., 2014), air layers between and on the outside of the clothing become even more important (G. Havenith, 2001). Each clothing layer has a still air layer attached to its outer surface that can be up to 6mm thick (12 mm total between two surfaces), outside of this area the air is not bound and will move due to temperature gradients (G. Havenith, 2001). When multi-layer clothing ensembles are considered, the total insulation will be much greater than the insulation of the material layer alone, as shown in Figure 7-1 below.

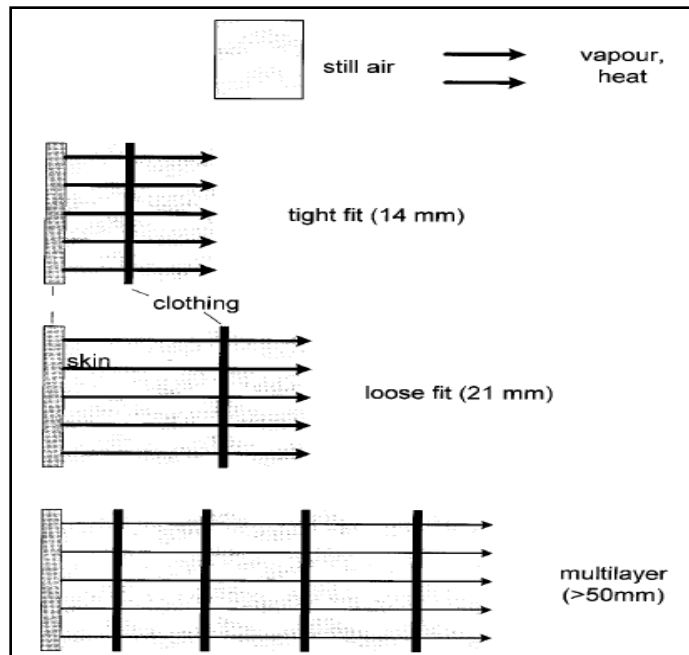


Figure 7-1. Schematic representation of fabric and air layer contribution to total thermal and evaporative heat transfer resistance (G. Havenith, 1999).

Figure 7-1 illustrates the impact of a looser fit garment which increases the air gap volume thickness from 14 mm in a tight fit, to 21 mm. The multi-layer depiction is representative of a structural firefighter turnout ensemble as the first layer reflects the base layers (stationwear) worn by the firefighter underneath the three layer (outer shell, moisture barrier, and thermal liner) base composite. The total insulation of the garment does not add up, however, to the number of layers multiplied by 15mm (12mm trapped air + 3mm per layer) as it is not a summative property (G. Havenith, 2001). Clothing design, body shape, and fit do not allow the clothing layers to be separated enough to enclose such air layers throughout the entire ensemble. Instead, air layers should be characterized in relation to garment fit (tight or loose) rather than size (Frackiewicz-Kaczmarek et al., 2014). With a

tighter fit garment, less air is included compared to a looser fit, hence the justification to explore tighter fitting materials in structural firefighter turnouts.

In addition, the movement of the wearer and the external air speed conditions also play a role in air gap volume. Air movement through wind disturbs the outer air layers of the ensemble as it enters through clothing openings, or through the fabric itself, depending on fabric air permeability (G. Havenith, 2001). Body motion of the wearer also creates movement in the air layers, but in a different manner. Wearer activity works to pump air between different clothing compartments within the ensemble, forcing the exchange with the environment, known as "pumping" or the "bellows effect." Wind mostly affects the surrounding air layer and the layer directly underneath the outer garment, whereas body motion affects both the enclosed and surrounding air layers (G. Havenith, 2001). These concepts are illustrated in Figure 7-2.

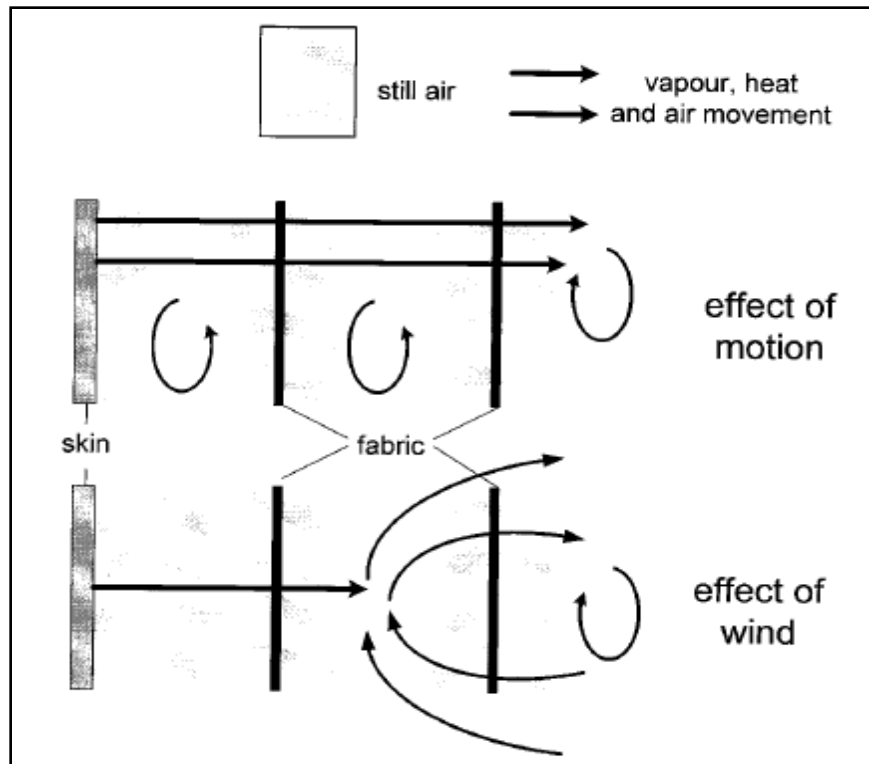


Figure 7-2. Effect of body motion and wind on the surface and trapped air layers of multi-layer clothing systems (G. Havenith, 1999).

In summary, air gap volume in multi-layer clothing ensembles, such as structural firefighter turnouts, plays as much of a role, if not more, than the clothing materials themselves in determining the heat loss properties of the system. In the past, bench level material studies have been conducted (Ertekin & Marmarali, 2011; Hes & de Araujo, 2010; Supuren, Oglakcioglu, & Ozdil, 2011) to examine air gap thickness but there is less knowledge regarding the impact of air gap volume on the three-dimensional human body when worn as a garment. It is important to gain a better understanding of how air gaps impact the overall heat loss in structural firefighter turnouts. Further, it is vital that modifications to

the garment design, such as tighter (closer) fitting materials which reduce the air gap volume of the microclimate, be explored to improve the physiological comfort of the firefighter in order to reduce incidents of heat and cardiovascular strain.

7.2 Experimental Methodology

To determine the impact of air gap volume in structural firefighter turnout ensembles, a combination of fabric and garment level methods were used. To assess the existing air gap volume in the base composite layers, THL measurements were performed on the material level, using a sweating guarded hot plate, and the garment level, using a sweating thermal manikin. Further analysis was conducted to determine how fabric thickness, air permeability, and garment air gap volume related to manikin THL.

As a clothing modification for potential heat loss and wearer comfort improvement, tighter fitting materials and garments were explored including a tight fit moisture barrier and a stretch knit long thermal underwear as a thermal liner replacement. These garments were evaluated on the sweating thermal manikin and 3D body scanner to determine how air gap volume affects heat loss in multi-layer clothing systems.

7.2.1 Materials

All base layer (outer shell, moisture barrier, and thermal liner) fabrics used in this study were held constant. The materials of the tight fit moisture barrier and thermal underwear garments differed only. Below, each material and/or garment is discussed in detail.

7.2.1.1 Single Layer Base Composite Materials

The outer shell, moisture barrier, and thermal liner layers were individually evaluated for THL (plate and manikin), fabric thickness, fabric weight, air permeability, and garment air gap volume. The outer shell consisted of a Polybenzimidazole (PBI®) and para-aramid blend, the moisture barrier was a Polytetrafluoroethylene (PTFE) laminate aramid, and the thermal liner was two layers of a nonwoven aramid batting quilted to an aramid facecloth. Material details and fabric properties for each individual base composite layer can be found in Table 7-1 below.

Table 7-1. Material structure and fabric properties of individual base composite layer suits.

Garment Layer	Material Structure	Fabric Weight (oz/yd²)	Thickness (mm)	Air Permeability (cf/min/ft²)
Outer Shell	PBI Matrix 60% Para-Aramid/40% PBI	7.16	0.4	11.32
Moisture Barrier	PTFE Laminate Aramid Crosstech	4.8	0.34	0
Thermal Liner	Caldura SL 2L E89 100% Aramid Quilt	7.52	1.23	94.88

7.2.1.2 Tight Fit Moisture Barrier and Thermal Liner

Previous literature suggests that the introduction of stretch materials for a tighter fit reduces the air gap volume of the clothing system (Frackiewicz-Kaczmarek et al., 2014). To determine how a reduction in air gap volume, by using a tighter fitting moisture barrier, would impact heat loss and comfort, a proprietary stretch membrane material was fabricated

into a full garment including a front-zip jacket and pants. Figure 7-3 depicts this garment dressed on the sweating thermal manikin. Seam seal tape was used in the construction of the garment to ensure no liquid penetration could occur. Due to the extreme tight fit of this moisture barrier material and garment, the re-arrangement of the base composite was necessary when testing in a full turnout ensemble. The tight fit moisture barrier was tested on the sweating thermal manikin as a single independent layer (Tight Fit MB), with the full ensemble (OS+TL+Tight Fit MB) and with the knit thermal underwear layer as a replacement for the thermal liner (OS+Knit TL+Tight Fit MB) which is explained in more detail below. The same configurations were also assessed on the 3D body scanner to quantify the reduction in air gap volume.



Figure 7-3. Tight fit moisture barrier garment dressed on sweating thermal manikin.

In addition to the tight fit stretch moisture barrier garment, a substitute for the thermal liner was explored to further reduce the large air gap volume still existent in the clothing system. A 100% soft-knit Nomex constructed thermal underwear set was chosen as a thinner, closer fitting option. Figure 7-4 illustrates the top and bottoms of the thermal underwear which have greater stretch and a tighter fit than the traditional thermal liner due to the knit construction. This layer was tested along with the tight fit moisture barrier and outer shell in a nontraditional arrangement (OS+Knit TL+Tight Fit MB) on the sweating thermal manikin

for predicted THL. It was also evaluated on a human subject model using 3D body scanning to determine the air gap volume.



Figure 7-4. Knit thermal underwear top and bottoms used as tighter fitting thermal liner.

7.2.2 Procedures

7.2.2.1 Fabric Thickness and Weight

The fabric thickness and weight was measured for the individual base composite layers (OS, MB, and TL). Fabric thickness was measured according to ASTM D 1777, test option 1. Three specimens (20 x 20 inch) were measured with a thickness gauge (mm) at an applied pressure of 0.6 psi at various locations of the fabric to determine an overall average thickness. Fabric weight was measured according to ASTM D 3776, small swatch option. Three specimens (20 x 20 inch) were weighed on an analytical balance and the weight was

calculated in mass per unit area (oz/yd²). Results of fabric weight and fabric thickness are presented in Table 7-1 along with the material structure and air permeability.

7.2.2.2 Air Permeability

Air permeability of each individual base composite layer was measured according to ASTM D 737-12, using a Frazier Air Permeability tester. Ten measurements were taken on each fabric with a test area of 38 cm² and test pressure of 125 Pa (Paschal). The unit of measurement was cfm (cf/min/ft²) which represents the air flow through a fabric at a constant pressure drop. The test orifice diameter was adjusted for each fabric sample in order to obtain reliable and reproducible measurements for each fabric type. The average air permeability (cfm) was calculated from the ten measurements for each fabric. Results are presented in Table 7-1 along with fabric structure, thickness, and weight.

7.2.2.3 Sweating Guarded Hot Plate THL

The methodology for conducting the sweating guarded hot plate evaluations to determine fabric level THL can be found in Chapter 5, section 5.2.1.2. In this study, the fabric level THL was determined for each individual base composite layer (outer shell, moisture barrier, and thermal liner) in a standard 25°C/65% relative humidity according to ASTM F 1868-14, method C.

7.2.2.4 Sweating Thermal Manikin

The outer shell, moisture barrier, and thermal liner garment layers were each assessed individually for ensemble level THL on a sweating thermal manikin (Figure 7-5) according to the procedure described in Chapter 3, section 3.2.2. The tight fit moisture barrier, alone and in conjunction with the full turnout ensemble (OS+TL and OS+Knit TL), was evaluated

for predicted manikin THL. All garments were tested assuming a normal working condition, such as a vehicle extrication scenario, with boots, gloves, and a helmet. The manikin was dressed in a cotton t-shirt, athletic shorts, and socks as base layers, except for the tight moisture barrier configurations. Each garment was tested in two conditions: a static (standing with still air speed at 0.4 m/sec) and dynamic (walking with wind at 2 m/sec). Table 7-2 captures the sweating thermal manikin testing conducted in this study.



Figure 7-5. Outer shell, moisture barrier, and thermal liner garments tested for manikin THL on a sweating thermal manikin in a normal working condition scenario.

Table 7-2. Garments tested for THL on a sweating thermal manikin.

Garment	Number of Layers	Test Scenario	Test Conditions
Outer Shell	1	Extrication	Static & Dynamic
Moisture Barrier	1		
Thermal Liner	1		
Tight Fit Moisture Barrier	1		
OS+TL+Tight Fit MB	3		
OS+Knit TL+Tight Fit MB	3		

7.2.2.5 Three-Dimensional Body Scanning

While methods using sweating thermal manikins measure the overall effect of fabric and air layers on thermal and evaporative resistance to heat transfer, the determination of localized effects is limited by the manikin segmentation. In addition, this method does not provide any indication of the actual thickness, or volume, of the air gap between the clothing layers (Frackiewicz-Kaczmarek et al., 2014). Instead, 3D body scanners may be used to determine the thickness and volume of the air gap between the body and the clothing layer. In this study, a Size Stream 3D body scanning booth (Figure 7-6) and desktop application were used to measure the air gap of the outer shell, moisture barrier, and thermal liner layers. In addition, the tight fit moisture barrier was measured alone, with a traditional fit thermal liner, with the knit thermal liner, and with the full ensemble configurations (OS+TL+Tight Fit MB and OS+Knit TL+Tight Fit MB). Each garment was scanned three times and an average surface area and volume were calculated. Sensor configuration for measurement includes 14 sensors placed at six angles around the body at seven different heights (“Size Stream,” 2016). The volume of the air gap was calculated by subtracting the volume of the

base layers or nude scan from the volume of each individual base composite layer or tight fit moisture barrier garment, respectively.

The garments were measured on a human subject model who closely fit the measurements of the sweating thermal manikin. The model had a pant size of medium, same as the manikin, and similar height (69in), chest (41in), and waist (32in) measurements. The "nude" scan of the model, wearing appropriate undergarments, is shown in Figure 7-7. It should be noted that fit of the garment on the manikin and the model are not identical. Fit does play a role in the air gap volume measured and, therefore, the amount of resistance provided by the air gap towards heat transfer.



Figure 7-6. Size Stream 3D body scanning booth (“Size Stream,” 2016).

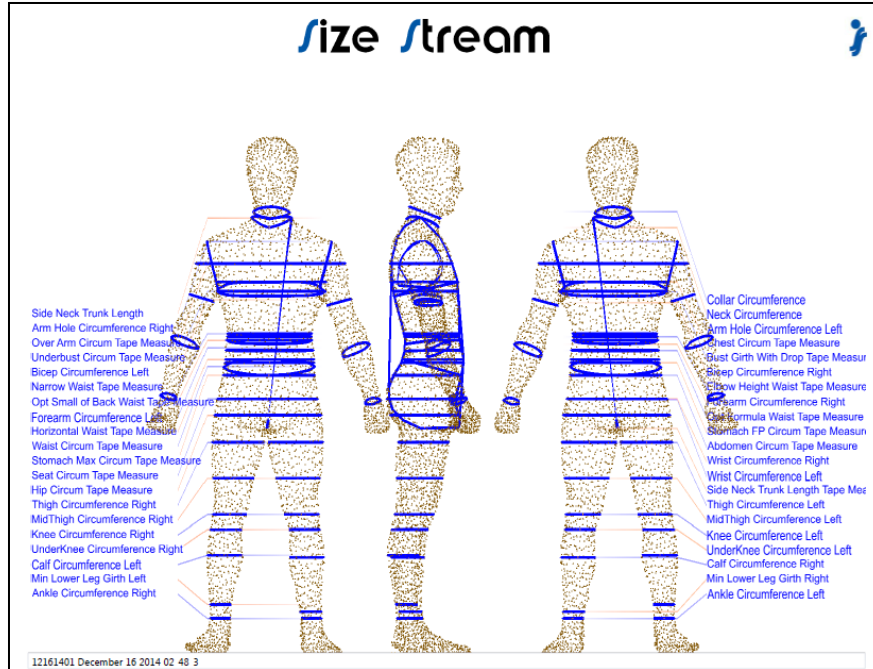


Figure 7-7. Nude body scan of human subject model.

The air gap volume and surface of each scanned suit was calculated by subtracting the volume, or surface area, of the base layers scan (t-shirt and athletic shorts) from each individual layer garment volume, or surface area. For the tight fit moisture barrier, the nude scan was subtracted as base layers could not be worn due to the tight fit. The air gap distance (mm), was calculated according to Equation 7.1.

Equation 7.1 Air Gap Distance

$$A_{gap} = \frac{V_{airgap}}{SA_{nude}}, \text{ where:} \quad (7.1)$$

A_{gap} = average distance between the base layer/nude body and the clothing layer over the surface area of the body (mm),

V_{airgap} = volume of clothing layer minus volume of base layer/nude body (cm³), and

SA_{nude} = surface area of the nude human subject model (with underwear) (cm^3).

7.2.3 Statistical Analysis

To determine the statistical significance of the measured differences in predicted manikin THL, compared to the baseline control, two-sample t-tests, assuming equal variances, were performed. All data was tested for normalcy and normal distributions were confirmed through a probability plot and the Anderson-Darling test statistic. A one-way ANOVA was conducted with each data set (for each test condition) to determine if significant differences were present. If differences were identified between the results, t-tests were carried out. All sets of data in this study showed significant differences, therefore, t-tests were conducted comparing each suit configuration to the control, and all other suits, for each of the two test conditions. A p-value less than 0.05 indicates a significant difference between the suits.

Further analysis was conducted for the fabric thickness, air permeability, and air gap volume. Pearson's correlation coefficients were used to determine if significant relationships existed between manikin THL and other factors including: air gap volume, air gap surface area, air gap distance, fabric thickness, and air permeability. A p-value less than 0.05 indicates a significant relationship between factors.

7.3 Results

7.3.1 Single Base Composite Layers

The outer shell, moisture barrier, and thermal liner layers were evaluated for fabric weight, thickness, and air permeability. These results are presented in Table 7-1. The thermal

liner layer was the thickest (1.23 mm) and the heaviest (7.52 oz/yd²) but had the highest air permeability (94.88 cfm). The moisture barrier was the thinnest and lightest weight material but was impermeable (0.00 cfm) to air. The outer shell was similar in weight to the thermal liner (7.16 oz/yd²) but much thinner (0.4 mm). The permeability of the outer shell was quite low (11.32 cfm) due to its tight weave structure which provides adequate impact penetration resistance against sharp objects.

Fabric THL was conducted for each base composite layer individually on the sweating guarded hot plate. The total thermal resistance (R_{ct}) and apparent total evaporative resistance (R_{et}^A) were analyzed because these values include the resistance to heat transfer through the fabric system, including the surface air layer. The THL (Q_t) in W/m² for each fabric layer was calculated as an indicator of the combined dry and wet heat loss through the fabric. Table 7-3 gives the results from the sweating guarded hot plate for each base composite layer.

Table 7-3. Fabric level thermal insulation, evaporative resistance, and THL of the base composite layers.

Fabric Sample	R_{ct}	R_{et}^A	Q_t
Outer Shell	0.091	0.012	522.7
Moisture Barrier	0.08	0.01	649.7
Thermal Liner	0.129	0.012	461.6

The thermal liner layer had the highest thermal insulation and resistance to dry heat loss, followed by the outer shell and moisture barrier. The moisture barrier had the lowest

evaporative resistance of the three layers and the highest THL at 649.7 W/m^2 . Further testing was necessary on the manikin level to determine how the addition of air layers in a three-dimensional garment impacts heat loss.

Predicted manikin THL, calculated in the standard $25^\circ\text{C}/65\%$ relative humidity environment, was conducted for each base composite layer garment on the sweating thermal manikin. Each garment was tested in a static condition and a dynamic condition. The manikin was dressed with the base layers, single layer garment, helmet, gloves and boots (Figure 7-5). The overall manikin THL of each layer, in both test conditions, is provided in Chapter 6, Figure 6-1.

Manikin THL results showed there were statistically significant differences between all three individual layer garments in the static condition, with the moisture barrier having the lowest heat loss, followed by the outer shell, and thermal liner. In the dynamic test condition, differences between suits were more pronounced but not statistically significant. The outer shell had the lowest heat loss in this condition, followed by the moisture barrier and thermal liner. The thermal liner's high THL values may be explained by inherent fabric properties, such as thickness and air permeability, or by air gap volume as it is worn as the closest layer to the body.

The outer shell, moisture barrier, and thermal liner garments were scanned on a human subject model for their size, surface area, and volume using a Size Stream body scanning booth. Table 7-4 depicts the surface area, air gap volume, and air gap distance for each single layer garment.

Table 7-4. 3D body scanning results of each single layer base composite garment.

Garment	Surface Area (cm²)	Air Gap Volume (cm³)	Air Gap Distance (mm)
Outer Shell	10274.2	86359.7	47.8
Moisture Barrier	9041.9	67207.0	37.2
Thermal Liner	8858.6	71803.0	39.7

The outer shell had the largest surface area, air gap volume, and air gap distance, followed by the thermal liner and moisture barrier. These findings are not surprising as the individual layers were separated from a traditional structural firefighter turnout with the outer shell constructed to be the outermost layer, reflecting the largest surface area and air gap volume. The thermal liner is a thick, stiff material contributing to its lack of conformity to the body and the larger air gap distance, compared to the moisture barrier. The moisture barrier is thinner and lighter weight, allowing it to drape closer to the body, when worn on its own, outside of the typical three layer ensemble. The moisture barrier layer had the smallest air gap volume and thickness.

The thermal liner had the highest predicted manikin THL despite its thickness and fabric weight, opposite of the fabric level plate THL results, in which it had the lowest THL of the three layers. To further analyze the air gap volume data and determine how fabric properties relate to manikin level THL, Pearson's correlation coefficient was determined for these factors. Table 7-5 shows the results for each test condition.

Table 7-5. Pearson's correlation coefficients for predicted manikin THL of single base composite layer garments.

Measurement	Static THL		Dynamic THL	
	r	p-value	r	p-value
Fabric Thickness (mm)	0.987	<0.1	0.657	0.54
Air Permeability (cfm)	0.991	<0.01	-0.932	0.236
Air Gap Distance (mm)	-0.06	0.96	0.53	0.65

Results of the body scanning air gap distance analysis show no correlation between air gap and manikin THL for natural convection in the static or dynamic test condition. The relationship between manikin THL and fabric thickness, however, did demonstrate a strong, positive, and significant ($p < 0.1$) correlation, for the static THL data, indicating that as thickness increases, so does THL. This conclusion does not make sense, however, as clothing insulation principles demonstrate the opposite, that as fabric thickness increases, heat loss decreases. Therefore, fabric air permeability was analyzed as a better indicator.

Figure 7-8 illustrates the correlation between garment level static THL of each base composite layer and fabric air permeability. Pearson's correlation coefficient showed a strong ($r = 0.991$), significant ($p < 0.01$) correlation between predicted manikin THL of individual garment layers and fabric air permeability. These results indicate that air permeability significantly influences heat loss more so than air gap distance or fabric thickness for the individual base composite layers on the garment level.

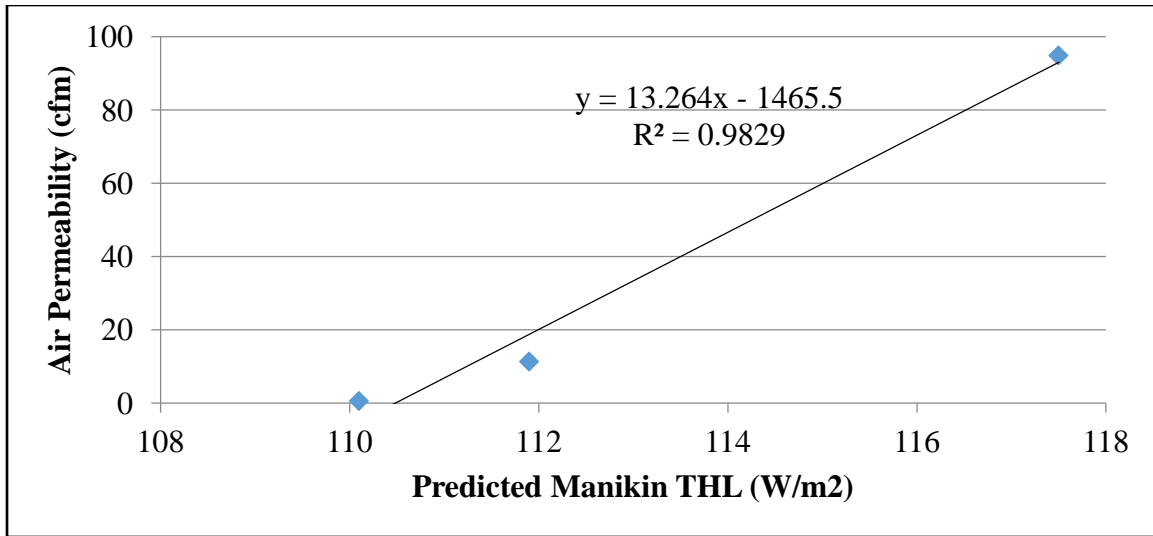


Figure 7-8. Correlation between predicted manikin THL and fabric air permeability in the static test condition.

7.3.2 Tighter Fitting Structural Turnout

Although air gap distance was not a strong predictor of manikin THL for each individual base composite layer, further research was necessary in the multi-layer clothing system. The implementation of tighter fit as a design modification for heat loss improvement was explored through the use of a stretch membrane garment and a set of knit thermal underwear as potential substitutes for the moisture barrier and thermal liner layers, respectively. The tight fit moisture barrier was tested by itself (Tight Fit MB), in conjunction with a traditional turnout ensemble (OS + TL + Tight Fit MB), and with a tighter fit thermal liner substitute (OS + Knit TL + Tight Fit MB). Evaluations were conducted on the garment level including predicted manikin THL in two test conditions (static and dynamic) and 3D body scanning of each ensemble configuration. Figure 7-9 illustrates the comparison of

manikin THL results between the traditional moisture barrier and the tighter fitting membrane.

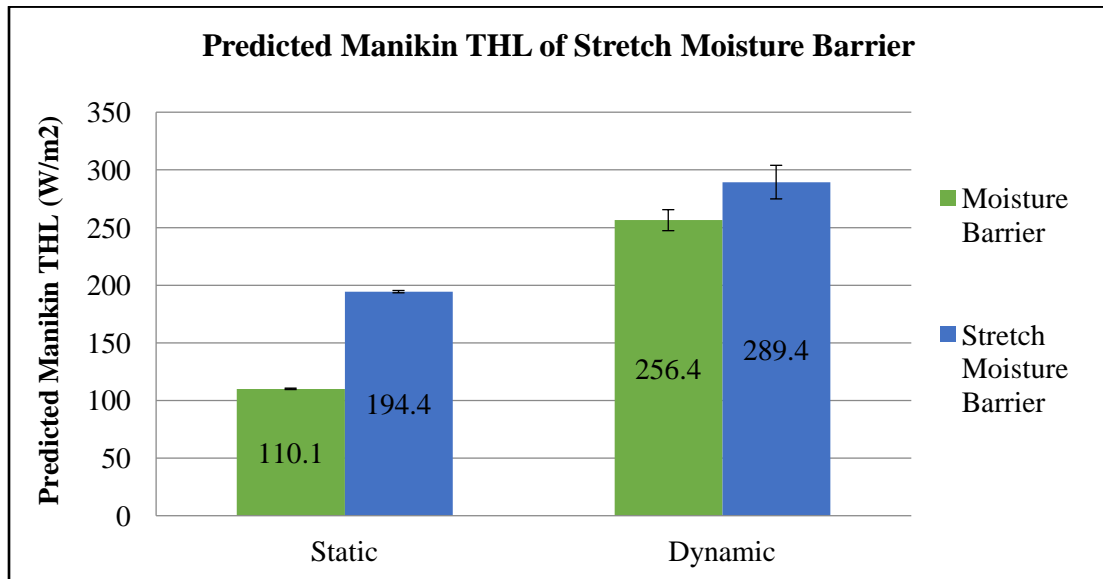


Figure 7-9. Predicted manikin THL comparison between traditional and tight fitting moisture barriers.

In both the static and dynamic test conditions, the stretch moisture barrier with a tighter fit had significantly ($p < 0.05$) greater THL compared to the traditional moisture barrier. An increase of 84.3 W/m^2 was measured in the static condition alone, just by implementing a tighter fit and reducing the air gap volume by $29,578 \text{ cm}^3$ (moisture barrier = $62,207 \text{ cm}^3$; tight fit moisture barrier = $32,629 \text{ cm}^3$). In the dynamic condition, with walking and wind present, an improvement of 33 W/m^2 was detected. These results indicate a positive benefit for including tighter fit materials in the current turnout ensemble. The tight fit

moisture barrier was then tested in two full turnout configurations: first with the traditional thermal liner and outer shell layers; second with a tighter fitting knit thermal liner and traditional outer shell layer. These results, compared to the traditional control (OS+MB+TL), are shown in Figure 7-10 below.

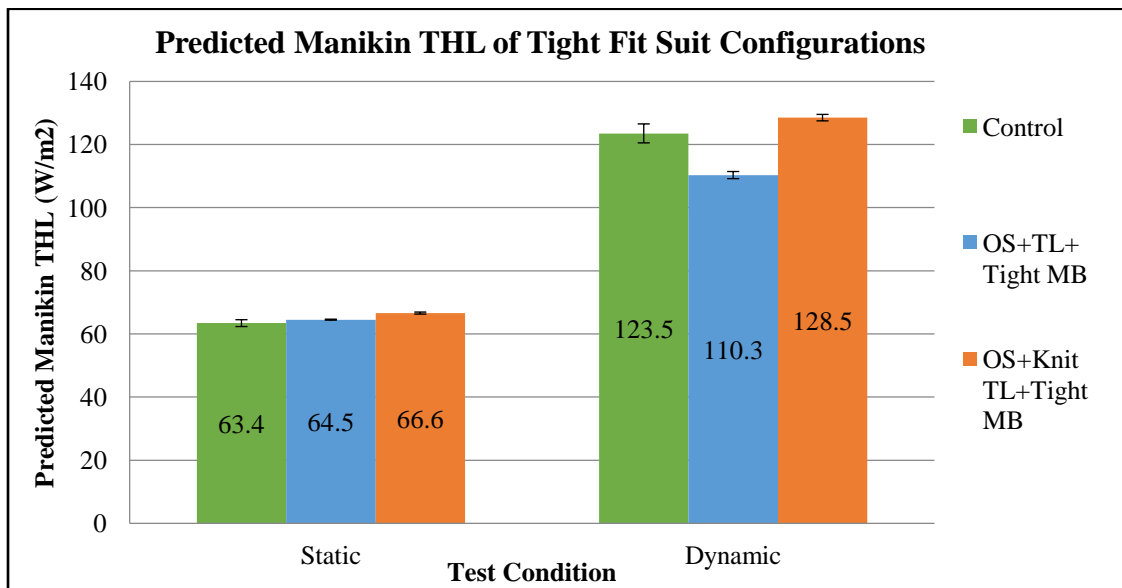


Figure 7-10. Predicted manikin THL comparisons of tight fitting suit configurations.

Even though significant increases in THL were found between the tight fit moisture barrier and the traditional moisture barrier when tested as single layers, the same benefits in multi-layer clothing ensembles were not measured. In the static condition, the OS+Knit TL+Tight MB had statistically significant increases in THL compared to the control configuration (OS+MB+TL) and traditional thermal liner. While statistically significant, the increase in THL of only 2-3 W/m² is not practically significant or meaningful for the wearer's

comfort. Realistically, there were negligible differences between the three configurations in the static condition, which is not surprising since material characteristics are similar, therefore natural convection through the fabric did not change.

In the dynamic test condition, however, greater differences between suits were measured. The OS+TL+Tight MB had significantly lower THL than the traditional control and OS+Knit TL+Tight MB. There was no significant difference between the control and the OS+Knit TL+Tight MB, meaning there does not seem to be a benefit for incorporating tighter fitting stretch materials in the turnout ensemble as they were in this experiment. A limitation of this research, however, is the traditional outer shell that was tested. The outer shell was not replaced with a tighter fitting material, therefore, it may have washed out any benefits of the reduced air gap in the inner layers.

To determine how air gap volume played a role in the heat loss data, 3D body scanning was conducted to quantify the reduction in air gap for the tighter fitting garments. The tight fit moisture barrier was scanned alone, with the traditional TL, and with the Knit TL. Additional scans were then conducted with the traditional OS layer on top of both TL configurations with the tight fit moisture barrier. The surface area, air gap volume, and air gap distance for each tight fit moisture barrier configuration are given in Table 7-6.

Table 7-6. 3D body scanning results of tight fit moisture barrier configurations.

Garment	Surface Area (cm²)	Air Gap Volume (cm³)	Air Gap Distance (mm)
Tight Fit Moisture Barrier	436.5	1991.2	1.1
Moisture Barrier	9030.3	64935.5	35.9
TL+Tight Fit MB	9052.2	69586.8	38.5
Knit TL+ Tight Fit MB	2093.4	13942.0	7.7
OS+TL+ Tight Fit MB	10503.2	91910.0	50.8
OS+Knit TL+ Tight Fit MB	10683.2	81900.4	45.3

Results in Table 7-6 illustrate the significant reduction in air gap volume with the tighter fitting, stretch moisture barrier. The traditional moisture barrier, used in the Control turnout, had an air gap volume of 64,935.5 cm³ between the clothing layer and the nude body, compared to the tight fit moisture barrier at just 1,991.2 cm³. The air gap distance was reduced by 34.8 mm when wearing the tight fit moisture barrier versus the traditional fit. This reduction in air gap supports the statistically significant improvements in predicted manikin THL illustrated in Figure 7-9.

When the traditional fit thermal liner was worn on top of the tight fit moisture barrier, the air gap distance was 38.5, compared to just 7.7 when wearing the tight knit thermal underwear as a substitute. When the traditional outer shell was worn, however, the difference in air gap distance between configurations was much smaller (5.5 mm) regardless of whether the tight fit moisture barrier was paired with a traditional thermal liner or knit thermal liner. This reflects the lack of significant improvement in manikin THL when the outer shell was worn. Therefore, further research should be done to develop and implement a tighter fitting outer shell replacement to reduce the overall air gap of the entire ensemble.

Pearson's correlation coefficient was determined for further analysis between manikin THL results and air gap volume data. Table 7-7 shows the results for each test condition and body scanning measurement.

Table 7-7. Pearson's correlation coefficients for tight fit moisture barrier configurations.

Measurements	Static THL		Dynamic THL	
	r	p-value	r	p-value
Air Gap Surface Area	-0.98	<0.05	-0.79	0.210
Air Gap Volume	-0.99	<0.05	-0.86	0.143
Air Gap Distance	-0.99	<0.05	-0.86	0.143

Results of the body scanning analysis, correlated to manikin THL, show a significant, negative relationship ($p < 0.05$) between air gap surface area and predicted heat loss in the static condition. As air gap surface area increased, manikin THL in the static test condition decreased. The same strong, inverse ($r = -0.99$) relationship was determined for air gap volume and distance when correlated with static THL. As the air gap size increased, the manikin THL significantly decreased in the static test condition. For the dynamic test condition, no significant relationships were established between manikin THL and air gap surface area or size. Strong, negative relationships were identified, but they were not statistically significant.

7.4 Discussion and Conclusion

The findings from this research have direct implications for designers, product developers, and manufacturers of functional performance clothing. Findings from fabric plate

THL results demonstrate the important role fabric weight and thickness play when evaluating heat loss on the sweating guarded hot plate test apparatus. The moisture barrier had the highest THL, despite its impermeability to air, as it is the thinnest and lightest weight material. The outer shell and thermal liner have similar evaporative resistances but the thermal liner has a much higher thermal resistance, leading to its lower overall THL when tested as a fabric on the plate.

In contrast to the fabric THL, the moisture barrier had the lowest overall heat loss and the thermal liner had the highest THL on the garment level. These results were unexpected due to the thermal liner's multi-layer construction. The thermal liner's high THL values were explained, however, by inherent fabric properties, in particular, air permeability. To determine the relationship between fabric and garment level THL of each of the three individual base composite layers, Pearson's correlation coefficient was determined. A strong, negative ($r = -0.883$) relationship was found indicating that as fabric plate THL increases, manikin level THL decreases. This relationship, however, was not determined to be statistically significant ($p = 0.311$). These results illustrate the limitations of measuring THL on the sweating guarded hot plate alone as it does not capture the effect of garment fit, air layers, and body motion on heat and mass transfer (Frackiewicz-Kaczmarek et al., 2014).

Results from this study suggest air permeability of individual fabric layers is the most influential factor when determining garment level heat loss performance of single layer systems. Although the thermal liner is the thickest of the three materials, it had the highest THL on the garment level because of its high air permeability compared to the outer shell and moisture barrier, which is impermeable.

The analysis of tighter fitting layers in the multi-layer protective clothing system did not show statistically significant improvements in overall THL. It should be noted, however, that these results mimic the findings in Chapter 6, section 6.3.3, when the moisture barrier and thermal liner layers were rearranged in the traditional composite. The significant reduction in THL, compared to the control, when incorporating the stretch moisture barrier directly against the skin may be due to the difference in temperature gradients created by placing the impermeable material closer to the body. A significant increase in THL is measured when the air gap volume between the thermal liner and moisture barrier layers is reduced by using a tight knit thermal underwear layer.

Body scanning data provided information regarding the surface area, air gap volume, and calculated air gap distance (mm) of each clothing ensemble, compared to the nude body scan for the tight fit moisture barrier configurations. It was determined that for the static manikin THL, there were strong, inverse relationships between air gap size and heat loss through the ensemble. As air gap surface area, volume, and thickness increased, the THL of the clothing system decreased. Specifically, when the traditional thermal liner and outer shell layers were added to the tight fit moisture barrier. This research indicates that a reduction in air gap volume by using tighter fitting garments significantly improves heat loss through the clothing system. However, if all layers in the ensemble are not significantly reduced to fit closer to the body, the benefit of increased heat loss is not realized. This was demonstrated by the lack of heat loss improvement when the traditional outer shell was worn on top of the tight fit moisture barrier and knit thermal underwear layers.

Therefore, it should be noted that a limitation of this experiment was the lack of stretch or air gap volume reduction in the outer shell layer, as the traditional layer was worn for all configurations. Future research should include implementation of stretch materials and a tighter fit in this layer, as well, to determine if an overall air gap reduction in the entire ensemble leads to significant heat loss improvements.

8 Implementation of Clothing Modifications through Functional Design for Heat Loss Improvement in Structural Firefighter Turnout Prototypes

8.1 Introduction

Functional clothing can be defined as clothing which is, "specifically engineered to deliver a pre-defined performance or functionality to the user, over and above its normal functions," (Gupta, 2011, p.321). One category of functional clothing is that which serves to provide a protective purpose. Structural firefighter turnouts are an example of functional clothing which exists to protect the user during firefighting activities. For firefighters, thermal protection from heat and flame is the first priority. Protection from water, due to steam burns, and sharp objects is also necessary, hence the need for a three layer clothing assembly in order to provide multiple types of protection. With multiple layers, however, comes increased physiological strain on the wearer as the added weight and bulk creates the need for more effort to be exerted by the body to perform similar tasks. The multi-layer clothing construction hinders the ability of the wearer to release excess body heat. The firefighter is left to battle the heat from the external fire source as well as his or her own internal body heat.

While thermal protection is the greatest priority for firefighter turnout designs, the current level of protection comes with a steep price. It does not serve the wearer well to protect from one threat to the point that another is created, in this case, heat stress. Therefore, improvements must be made to increase heat loss within the clothing system but, not at the

cost of sacrificing thermal protection. In order to solve this problem, functional design for protective clothing may be turned to as a guideline for managing this process.

In this research study, the results and conclusions from the previously explored design modifications (Chapters 3-7) were combined to create revolutionary modern turnout prototypes that provide comfort performance above and beyond what is currently on the market today (control suit). Simultaneously, maintaining the firefighter's need for adequate thermal, chemical, and liquid protection is necessary. To determine which design modifications should be incorporated into structural firefighter turnout prototypes, the functional design process and systems engineering tools were used in the down selection phase.

8.2 Functional Design Process

The functional design process (Figure 8-1) is one in which the designer goes step-by-step, from an initial design idea all the way to evaluating the final design prototype (Watkins, 1984). The functional design process outlined by Watkins in her book, "Clothing The Portable Environment," involves the following seven steps:

1. Design Request Made
2. Design Situation Explored
3. Problem Structure Perceived
4. Specifications Described
5. Design Criteria Established
6. Prototype Developed
7. Design Evaluation of Prototype

FUNCTIONAL CLOTHING DESIGN PROCESS AND STRATEGY SELECTION						
	2 Design situation explored	3 Problem structure perceived	4 Specifications described	5 Design criteria established	6 Prototype developed	7 Design evaluation
1 Request made	1.2 State general objective Brainstorming User interview and observation Visual inconsistency Literature search					
2 Design situation explored		2.3 Brainstorming Observation analysis Market analysis Literature search Identification of critical factors Definition of problem				
3 Problem structure perceived	3.2 Brainstorming Visual inconsistency Reassess critical factors		3.4 Activity assessment Movement assessment Impact assessment Thermal assessment Social-psychological assessment			
4 Specifications described	4.2 State objectives Check specifications against objectives	4.3 Reassess critical factors		4.5 Charting Ranking and weighting Prioritizing		
5 Design criteria established	5.2 State objectives Check criteria against objective	5.3 Identify critical factors	5.4 Literature review of assessment areas to check specifications		5.6 Materials testing technique evaluation Brainstorming Creative integration Solutions weighed against criteria	
6 Prototype developed	6.2 Visual inconsistency Identify objective User interview	6.3 Identify critical factors	6.4 Literature review of assessment areas	6.5 Rank order specifications		6.7 Specification testing User satisfaction

Figure 8-1. Functional clothing design process and strategy selection (Watkins, 1984).

The functional design process begins with a design request or complaint from the individual or industry wearing the specified garment. During this step the general problem is identified, the design situation is explored, and multiple directions for investigation are

identified (Watkins, 1984). In this research study, the problem expressed by the fire service industry was excessive heat strain which accounts for the majority of firefighter injuries and fatalities.

Once the areas of investigation have been established, the designer moves to stage two of the process in which the design situation is thoroughly explored. In this stage, the designer isolates critical factors that are potentially causing the problem (Watkins, 1984). A literature search (Chapter 2) is typically completed in this phase to evaluate what design aspects exist, have been evaluated, and are useful. This stage should end with a specific definition of the problem.

The third step in the functional design framework is to perceive the problem structure. Assessments are performed of the movement, activity, impact, and thermal functions of the garment (Watkins, 1984). Data is gathered on the critical design factors at the completion of this step. From here, specifications can be described in stage four (Chapters 3-7). In this stage, a garment is designed with specifications that do not interfere with the wearer's task and may actually promote ease of wear and comfort (Watkins, 1984). From these specifications, design criteria are developed in step five. Charting, ranking, and weighing of specifications occurs to establish the priority of these applications within the design (Watkins, 1984). A matrix is often used in this step to determine which design criteria are in conflict with one another and which are of greatest priority for implementation. The outcome of this step is a list of specifications ranked according to importance, that are ready for prototype development (Watkins, 1984).

The sixth step in the functional design process is to develop the prototype(s). Within this stage, tests are performed, both textile testing and construction evaluation, to ensure the prototype will meet the design criteria (Watkins, 1984). Once the prototype has been developed, it must be evaluated to ensure it meets the necessary improvements and solves the initial problem identified to the best of its ability. This occurs in the last stage of the functional design process known as design evaluation. Within this stage, specification testing occurs to obtain objective data of the prototype's ability to meet the design criteria (Chapters 8-10). This stage also involves subjective data which is gathered through user satisfaction evaluations (Watkins, 1984).

The challenge to the process of functional design is the opportunity to intermingle the elements of both textile materials and apparel constructions to create the optimum garment to meet the specific performance properties required by its use. The functional design process serves as an operational framework for identifying and developing a prototype that will improve the issue of heat stress currently experienced by the firefighter.

For this particular research concerning structural firefighter turnouts, the challenge is not understanding the design request made or exploring the situation thoroughly. There is sufficient literature on these issues. The third step in the functional design process is where the challenge begins with assessing the problem structure. The designer must determine which areas of functionality should be evaluated and what improvements can be implemented. This however, is not the most challenging stage. The incorporation of many different design modifications and material additions can be overwhelming for the researcher. For example, examining the case of clothing ventilation alone, the choice must be

made between the type of ventilation (active or passive), the affects of pumping and forced convection, type of design (zipper, mesh, garment opening, etc.), placement within the garment, and so on. This is only one technological improvement that must be managed within the functional design process. This is where step five of the process begins to meet the challenge by creating an interaction matrix of the various design specifications.

8.2.1 Interaction Matrix

An interaction matrix shows specifications that are in direct conflict by denoting them with a "0", specifications that require accommodation to be in the same design as a "1", and specifications that create no conflict as a "2". This matrix can be used to consider structural firefighter turnouts. The design modifications including ventilation, strategic layering, modularity, and air gap volume reduction can be evaluated together for their ability to coincide in the same design. An example of a design matrix for a sleeping ensemble is shown in Table 8-1.

Table 8-1. Example interaction matrix for a sleeping ensemble (Watkins, 1984).

Interaction Matrix										
	1	2	3	4	5	6	7	8	9	10
1. Cover torso completely		2	2	2	1	2	2	2	2	2
2. Cover limbs completely			2	2	1	2	2	2	2	2
3. Cover feet completely				2	2	2	1	0	2	2
4. Provide head covering					1	1	1	0	2	2
5. Secure garment openings at sleeves and neckline						1	1	1	2	2
6. Provide adjustable closures for easy on/off operation								2	1	2
7. Garment should be comfortable								1	2	2
8. Garment should be aesthetically pleasing									2	2
9. Garment should be machine wash and dry										2
10. Garment should be capable of mass production										

From this step in the functional design process, decisions can be made regarding which technological innovations to include in the final prototype design. The rest of the process involves creating these prototypes and evaluating them for their final performance.

An interaction matrix (Table 8-2) was developed for this study to better inform the down selection phase of the product development process. This tool allows the researcher and designer to determine which modifications can be included in harmony in the same design versus those that will not possibly work in conjunction with one another due to a specific limitation.

Table 8-2. Interaction matrix for structural firefighter turnout prototypes.

Interaction Matrix for Structural Turnout Prototype Designs										
	<i>1</i>	<i>2</i>	<i>3</i>	<i>4</i>	<i>5</i>	<i>6</i>	<i>7</i>	<i>8</i>	<i>9</i>	<i>10</i>
1. Active Zipper Ventilation	-	2	1	2	2	0	2	2	2	2
2. Active Vertical Ventilation	-	0	2	2	0	2	2	2	2	2
3. Passive Open Ventilation			-	2	0	0	1	0	2	2
4. Reduction of Thermal Liner				-	2	2	1	1	2	2
5. Single Layer OS Modular Suit					-	2	1	0	0	0
6. Multi Layer Modular Suit						-	2	1	2	2
7. Stretch Component Panels							-	1	2	2
8. Shape Memory Alloys (SMAs)								-	2	2
9. Phase Change Materials (PCMs)									-	2
10. Reflective/Heat Blocking Materials										-

The interaction matrix in Table 8-2 reflects design and material modifications explored within the larger Revolutionary Modern Turnout Project which this research was a part of. Material modifications are included in the interaction matrix as they were considered when developing the structural prototype turnouts. Those design modifications which showed promise from the ventilation, layering, and modular experimentations were proposed for inclusion in the prototype designs. These included the active zipper and vertical vents, passive open vents, single layer modular suit (OS only), multi-layer modular suit (OS+MB), and the reduced thermal liner in specific locations. The bulk reduction study (Chapter 5) demonstrated the detriment of additional bulk but did not show significant improvements in heat loss when specific reinforcements were removed. Similarly, Chapter 7 illustrated the benefit of reduced air gap volume in a single layer system (moisture barrier) but not in a full multi-layer system due to the outer shell not being compressed. Instead, stretch panels and a

tapered, athletic fit were considered for incorporation into the next level revolutionary modern turnout designs. This design concept would provide a reduction in air gap volume by creating a tighter fitting suit, as well as, a potential increase in ergonomic function and range of motion through the incorporation of stretch materials.

The interaction matrix for this research identified those design concepts which would work together, but with some modification, and those which could not be incorporated in the same turnout system. For example, the ventilation systems could not be incorporated with a multi-layer modular system as they are fabricated through all three layers (i.e. zipper sewn into all three layers) and the modular system involves separating and removing individual layers for specific working conditions. Another example of direct conflict is the incorporation of shape memory alloys (SMAs), phase change materials (PCMs), and heat blocking materials in a single layer modular system as a minimum of two layers are necessary to incorporate these additional materials.

In addition, the matrix highlights necessary accommodations that must be made when combining two or more design concepts. For example, in order to reduce the thermal liner and incorporate SMAs, accommodations would be necessary in order to properly attach the SMAs and ensure they do not cause conduction burns with the reduction in thermal layers. Overall, however, the majority of the design and material innovations brought forth for incorporation in the prototypes may be implemented together with little modification necessary.

It should be noted that the material modifications (SMAs, PCMs, and reflective materials) were explored as part of the larger research project and are not within the scope of

this research. Unfortunately, the initial experimentation of these novel material advancements did not show promising results. Therefore, they were not proposed going forward in the product development process.

8.2.2 Digital Logic Decision Making Tool

While the interaction matrix from Watkins' functional design process was a helpful tool for determining which design modifications to incorporate and how to do so together, a separate tool was used for down selecting between various structural firefighter turnout prototype designs. Six initial prototype concepts were presented including: a venting design, reduced layers design, air gap reduction design, stretch material design, stretch material with layer reduction design, and a stretch material plus venting design. Each design concept was presented to the project research team and the digital logic decision making tool was used to assign numerical values by conducting comparisons for every pair of suits. Table 8-3 illustrates the digital logic tool used for this research study.

Table 8-3. Digital Logic tool for structural firefighter prototype selection.

n	Suit Option	1 & 2	1 & 3	1 & 4	1 & 5	1 & 6	2 & 3	2 & 4	2 & 5	2 & 6	3 & 4	3 & 5	3 & 6	4 & 5	4 & 6	5 & 6	Sum of Preferences	Relative Weight
1	Venting	2	2	2	2	2											10	22.2%
2	Reduced Layers	1					1	1	1	1							5	11.1%
3	Air Gap Reduction		1				2				1	2	1				7	15.6%
4	Stretch Materials			1				2			2			2	1		8	17.8%
5	Stretch+ RedLayers				1				2			1		1		1	6	13.3%
6	Stretch+ Venting					1				2			2		2	2	9	20.0%

From the digital logic decision making tool, the designer and researcher are able to identify those concepts that are of highest priority to carry forth into initial sample production. By ranking each suit against the other, an overall sum of preference can be calculated and the relative weight determined. This tool provides quantitative data allowing for a more objective decision to be made. Of the six prototype design concepts that were evaluated in this particular research, the venting design ranked highest, followed by the stretch components plus venting, the stretch components alone, the air gap reduction suit, and stretch plus reduced layers. The suit concept with the lowest score was the reduced layers only design.

The final prototype designs were communicated with the research project's industry partner. An on-site visit was conducted with the research and development team to ensure design and material details were clear and feasible. The finalized structural firefighter turnout prototypes are presented in the methodology section below.

8.3 Methodology

8.3.1 Structural Firefighter Turnout Prototypes

The interaction matrix and digital logic chart were used to select four finalized prototype designs that were fabricated into initial samples by an industry manufacturing partner. Table 8-4 below describes each prototype concept and indicates its material TPP compliance according to NFPA 1971.

Table 8-4. Structural firefighter turnout prototypes.

Prototype	Description	NFPA TPP Compliance
Control	Standard Super Deluxe Turnout Suit	Yes
1	USAR Suit – Control – liner System	No
2	Venting - zipper vents + vertical side seams	Yes
3	Stretch Components – tapered fit	Yes
4	Stretch Components + Venting + Reduced Thermal Liner Torso Layer	No

The same standard Control turnout model that was used throughout the research study was also used to compare against the structural turnout prototypes and is shown in Figure 8-2 below. The Control suit, and all other prototypes, were made of the same base composite materials that were held constant throughout this study and are described in Table 7-1.



Figure 8-2. Structural firefighter turnout Control garment.

A statistically significant improvement in THL of 34 W/m^2 was measured when the traditional three layer turnout was reduced to one outer shell layer (section 6.3.4). Therefore, the single layer modular approach was chosen to represent a USAR working condition and will consist of the Control suit with the liner system (moisture barrier and thermal liner) removed (Figure 8-3). This suit would be worn in working conditions where the threat of thermal exposure was not present and protection from harmful liquids or chemicals is not necessary as it consists of an outer shell layer only.



Figure 8-3. Single layer outer shell USAR turnout prototype coat with liner removed.

The venting concept (Figure 8-4) was a combination of the active zipper and active vertical vents combined as each showed a statistically significant improvement in heat loss in the walking test conditions (section 3.3.1). The vents were placed through all three layers of the base composite along the outer side seams of the coat and pants. In the turnout coat, the vents extend from the elbow patch on the sleeve of each arm, up to the armpit, and down the vertical side seam. In the pants, the vents may be zipped open down the entire length of the outer pant side seam. A modification to the pant pocket design had to be made in order to accommodate vertical zippers along the outer side seams. The side pant pockets were split into two, with one placed on either side of the zipper vent. The passive open vent concept was not carried forth into prototyping because of its large sacrifice to thermal, liquid, and chemical protection.



Figure 8-4. Active venting structural firefighter turnout prototype.

Although the tight fit moisture barrier and knit thermal liner did not show statistically significant improvements in THL when tested on the sweating thermal manikin (Chapter 7), a different approach to air gap volume reduction was implemented. A three layer stretch component panel was fabricated into the turnout coat in the areas highlighted in red illustrated in Figure 8-5. After the first sample prototype was received and tried on, an additional stretch panel was added to the pant gusset for increased range of motion (Figure 8-

6). In addition, a tapered, athletic fit was incorporated to further reduce the air gap volume and engage the stretch components.

The material components of the stretch panels consisted of a 100% Nomex IIIA single sided knit fleece fabric with one-way stretch, placed in the horizontal direction of the garment, in the outer shell and thermal liner layers. A proprietary stretch membrane was placed in the middle of the three layer component, between the fleece layers, to serve as a barrier against moisture. Fabric level testing was conducted to confirm the three layer stretch component met the minimum requirements for TPP according to NFPA 1971. Unfortunately, it reduced the fabric level plate THL to under 200 W/m^2 , a limitation for heat loss.



Figure 8-5. Sketch of stretch component panels in structural turnout prototype.



Figure 8-6. Stretch component structural firefighter turnout prototype.

Finally, a combination of the venting and stretch components were incorporated with a reduction of the thermal liner in the torso of the coat to produce a revolutionary turnout prototype (Figure 8-7). Fabric level TPP testing was conducted on the base composite with a reduced thermal liner. In order to meet the minimum NFPA requirement for TPP with a reduced thermal liner, however, a flame retardant t-shirt or stationwear shirt base layer would need to be considered as part of the turnout ensemble. A comprehensive base layers study was outside the scope of this research. Instead, this concept was incorporated in a minimal

portion of the turnout but technically, would not meet NFPA compliance for TPP performance.



Figure 8-7. Revolutionary combo structural firefighter turnout prototype.

8.3.2 Procedures

Each firefighter turnout prototype was assessed for heat loss on the sweating thermal manikin, scanned in a Size Stream 3D body scanner to determine air gap volume, and modeled for predicted physiological comfort performance.

8.3.2.1 Sweating Thermal Manikin THL

The prototypes were each assessed for ensemble level THL on a sweating thermal manikin (Figure 8-8) according to the procedure described in Chapter 3, section 3.2.2. All garments were tested assuming a normal working condition, such as a vehicle extrication scenario, with boots, gloves, and a helmet. The manikin was dressed in a cotton t-shirt, athletic shorts, and socks as base layers. Each garment was tested in two conditions: a static (standing with still air speed at 0.4 m/sec) and dynamic (walking with wind at 2 m/sec).



Figure 8-8. Control structural firefighter turnout tested in a vehicle extrication scenario on the sweating thermal manikin.

It should be noted that all previous manikin THL results were predicted in the standard NFPA conditions of 25°/65% relative humidity in order for comparisons to be made

on the fabric level. For the turnout prototypes, predicted manikin THL results were calculated in both the standard 25°/65% relative humidity conditions, as well as, a 35°C/35% relative humidity environment. The 35°C/35% relative humidity environmental condition was chosen in accordance with the protocol for the human subject wear trial (Chapter 9). Analyzing the data under the same environmental conditions allowed correlations between measured physiological results and garment THL to be conducted in order to establish a benchmark for the amount of heat loss required to improve wearer comfort.

8.3.2.2 3D Body Scanning

The turnout prototypes were measured on a human subject model according to section 7.2.2.5. The surface area and air gap volume were used to calculate air gap distance. This data quantified the reduction in air gap volume, specifically for the stretch component and revolutionary combo prototypes, which implemented stretch materials and a tapered, athletic fit.

8.3.2.3 Virtual Human Modeling

To determine the predicted physiological responses when wearing each firefighter turnout prototype, the raw thermal insulation and evaporative resistance data were modeled according to the methodology described in Chapter 4, section 4.3.2. The modeling protocol used for the prototypes differed from the protocol used in Chapter 4, Table 4-1. Instead, the prototypes were modeled in the same protocol as the human subject wear trial (Chapter 9) which is reflected in Table 8-5.

Table 8-5. Physiological modeling of firefighter turnout prototypes.

Temperature (°C)	Relative Humidity	Length of Protocol	Activity Level	Activity Type
35	35%	100 minutes (20 minute work/5 minute rest cycles)	5 Mets	Standing

8.3.3 Statistical Analysis

To determine the statistical significance of the measured differences in predicted manikin THL between prototypes and compared to the control, two-sample t-tests, assuming equal variances, were performed. All data was tested for normalcy and normal distributions were confirmed through a probability plot and the Anderson-Darling test statistic. A one-way ANOVA was conducted with each data set (for each test condition) to determine if significant differences were present. If differences were identified between the results, t-tests were carried out. All sets of data in this study showed significant differences, therefore, t-tests were conducted comparing each prototype to the control, and all other prototypes, for each of the two test conditions (static and dynamic). A p-value less than 0.05 indicates a significant difference in THL between the control suit and the ventilated suit.

Pearson's correlation coefficients were conducted to determine if significant relationships existed between manikin THL and body scanning measurements including: air gap volume, air gap surface area, and air gap distance. A p-value less than 0.05 indicates a significant relationship between factors. Statistical significance for virtual heat strain modeling was determined by analyzing if each data point fell within two standard deviations

of the sample mean. This method of determining statistical significance was limited by the lack of repeated measures inherent to the modeling methodology.

8.4 Results and Discussion

8.4.1 Prototype Garment THL

THL results for the structural firefighter turnout prototypes were predicted in two different environmental conditions: the standard 25°C/65% relative humidity condition specified by NFPA 1971 for plate THL and a more realistic 35°C/35% relative humidity environment. Manikin THL predicted in the 35°C/35% RH environment better represents real life conditions a firefighter would be exposed to, particularly during a hot, dry summer day. These conditions were used in the human wear trial (Chapters 9 and 10) therefore, data was predicted in this condition in order to establish a relationship between physiological comfort performance and THL measured on a sweating thermal manikin (Chapter 11), in the same environment. It should be noted that in a 35°C environment, the air temperature is the same as the body's skin temperature therefore, no dry or convective heat loss is able to occur. In this condition heat loss comes from sweat evaporation.

Figures 8-9 and 8-10 illustrate the predicted manikin THL for the structural firefighter turnout prototypes in the 25°C/65% RH environment in the static and dynamic test conditions. The USAR, Vent, and Revolutionary prototypes had statistically significant ($p < 0.05$) improvements in predicted manikin THL in both test conditions, compared to the Control. The single layer outer shell USAR prototype had the greatest THL (103.8 W/m²) in the static test condition where natural convection through the fabric and garment openings is measured. This prototype performed similarly to the single layer outer shell garment in the

previous experimentation (Chapter 6, Figure 6-1). When walking and body motion were introduced into the test environment, the Vent prototype had the greatest THL at 260.4 W/m², an 83.3 W/m² improvement in heat loss. The addition of body motion introduced the pumping, or "bellows effect", in the dynamic condition which contributed to the Vent prototype having the greatest overall THL in this condition. The Vent prototype was a combination of the active zipper and active vertical vent designs investigated in Chapter 3. Combined they provided improvements in THL greater than either of them alone (Figure 3-2). The Revolutionary prototype was a combination of the Vent and Stretch prototypes. It had the second highest THL in both test conditions at 99.0 W/m² and 255.2 W/m², respectively. It performed similarly to the Vent prototype as it included the same active vent designs.

The Stretch prototype did not show a statistically significant improvement in THL in either test condition. In fact, the opposite was true in the dynamic condition, where the Stretch prototype showed a significant decrease in heat loss compared to the Control. The design concepts in the Stretch prototype were an overall reduction in air gap volume through the use of stretch panels and a tapered, athletic fit. These results confirm the conclusions in Chapter 7. Even with a closer fitting outer shell layer, a multi-layer reduction in air gap volume actually leads to a decrease in heat loss. A probable hypothesis of why this reduction occurs is the lack of convective air flow that is able to occur in between clothing layers when air gaps are significantly reduced below 8mm (Frackiewicz-Kaczmarek et al., 2014; Spencer-Smith, 1977).

In addition, another limitation of the Stretch prototype was its lower THL in the stretch panel zones. The THL of the three layer base composite, on the fabric level, was

263.4 W/m². Plate THL of the three layer stretch panel fabrics was 172.8 W/m², a significant reduction. The stretch panels were included from an ergonomic perspective. The added stretch allowed for a more tapered fit, reduced the air gap volume, and should provide greater range of motion for the wearer. This design concept should reduce the wearer's restriction of movement when performing certain tasks. The evaluation of ergonomics and range of motion was outside the scope of this dissertation but is a part of the larger Revolutionary Modern Turnout Project. Therefore, the performance of the Stretch prototype when evaluated for manikin THL was expected.

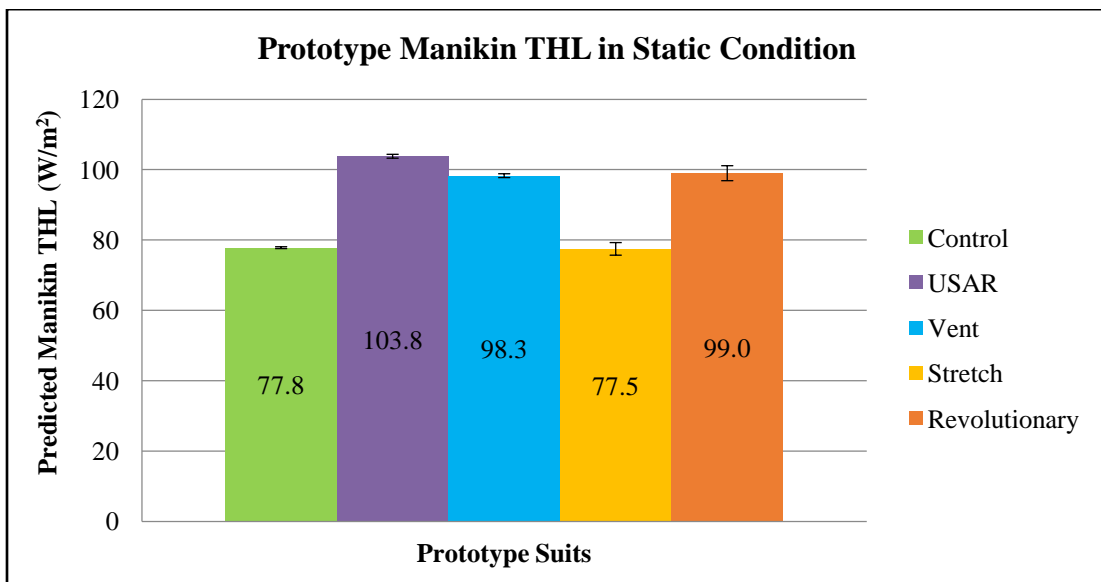


Figure 8-9. Predicted static manikin THL of prototypes in 25°C/65% rh environment.

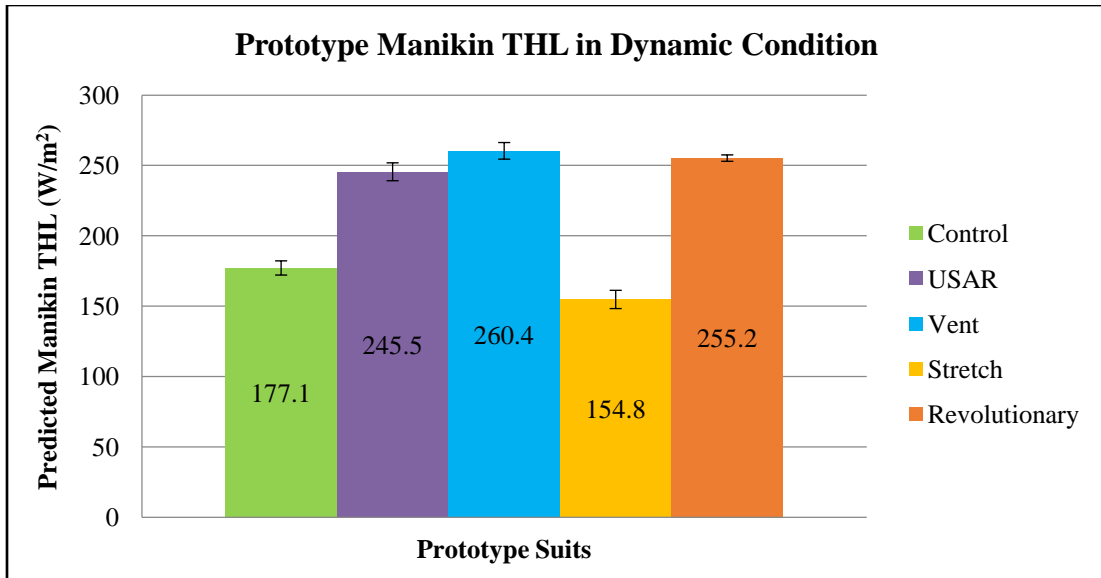


Figure 8-10. Predicted dynamic manikin THL of prototypes in 25°C/65% rh environment.

The Revolutionary prototype was a combination of the Vent and Stretch prototypes, along with a reduced thermal liner in the coat torso location. In the torso region of the coat (excluding the sleeves), the thermal liner batting layers were removed leaving the outer shell, moisture barrier, and facecloth layers only. Figure 8-11 shows the localized improvement in predicted manikin THL in this region when tested in a static condition. In the front region of the body, the middle torso segment had a 53.4 W/m² increase in THL and in the back region of the body, the middle torso had a 17.4 W/m² improvement, both of which are statistically significant. It cannot be determined, however, that this increase in heat loss is due solely to the reduction in thermal liner material layers. Instead, it is likely these improvements in heat loss are also due to the placement of the open active vents in the side seams of the coat and underarms. This conclusion is further confirmed by the similar performance of the

Revolutionary and Vent prototypes in both test conditions which were not significantly different from one another.

Manikin THL was then predicted in a 35°C/35% RH environment to determine the heat loss that would occur in the same environment as the human wear trial, which simulated a realistic vehicle extrication scenario. Heat loss diagrams of each structural firefighter turnout prototype, in the predicted 35°C/35% RH environment are included in Appendix E. Figures 8-12 and 8-13 illustrate the manikin THL in the static and dynamic test conditions for these environmental conditions. Again, it should be noted that all heat loss in this scenario occurred through evaporation as skin temperature and environmental air temperature were the same, which does not allow for dry heat loss to occur.

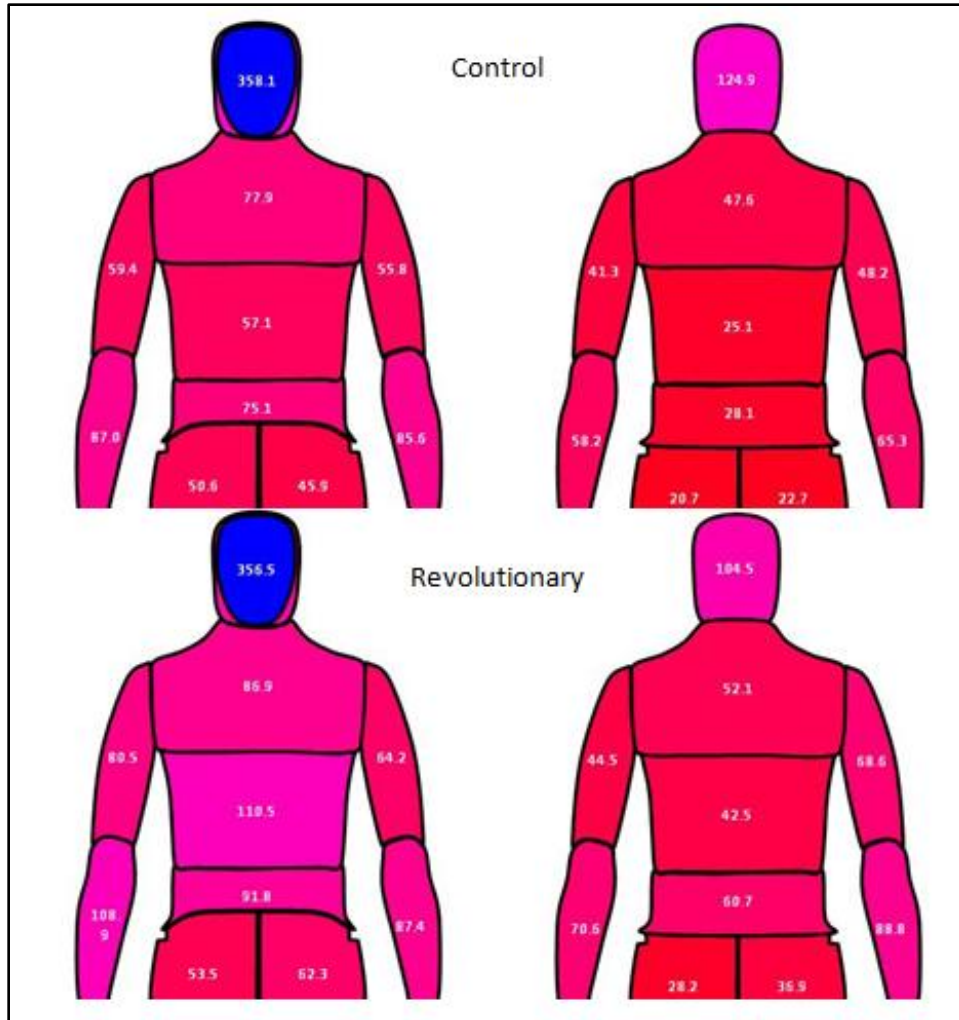


Figure 8-11. Isolated predicted manikin THL in static test condition of Control versus Revolutionary prototype in 25C/65% rh environment.

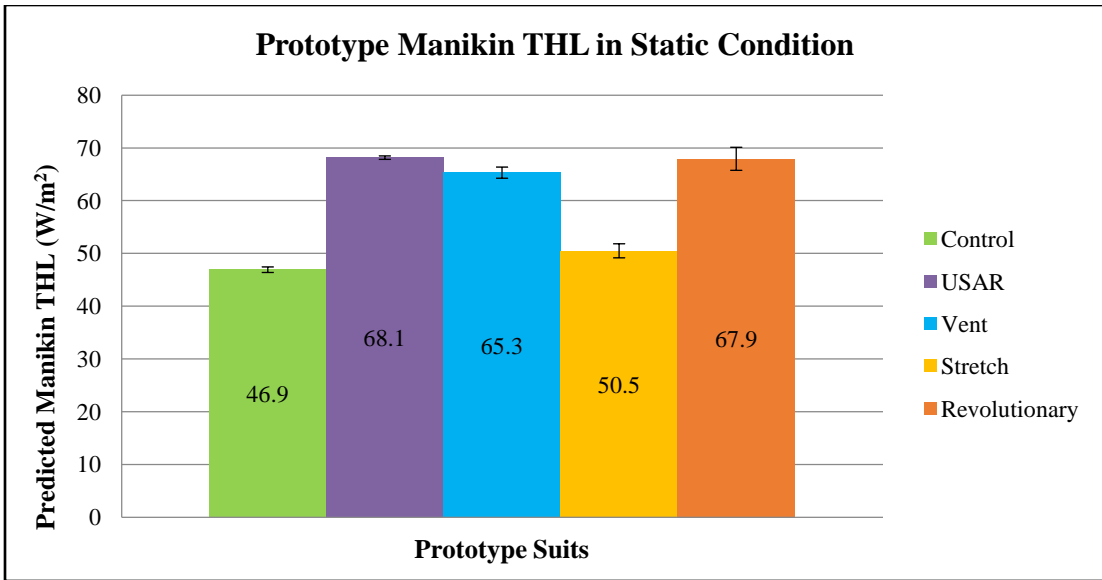


Figure 8-12. Predicted static manikin THL of prototypes in 35°C/35% rh environment.

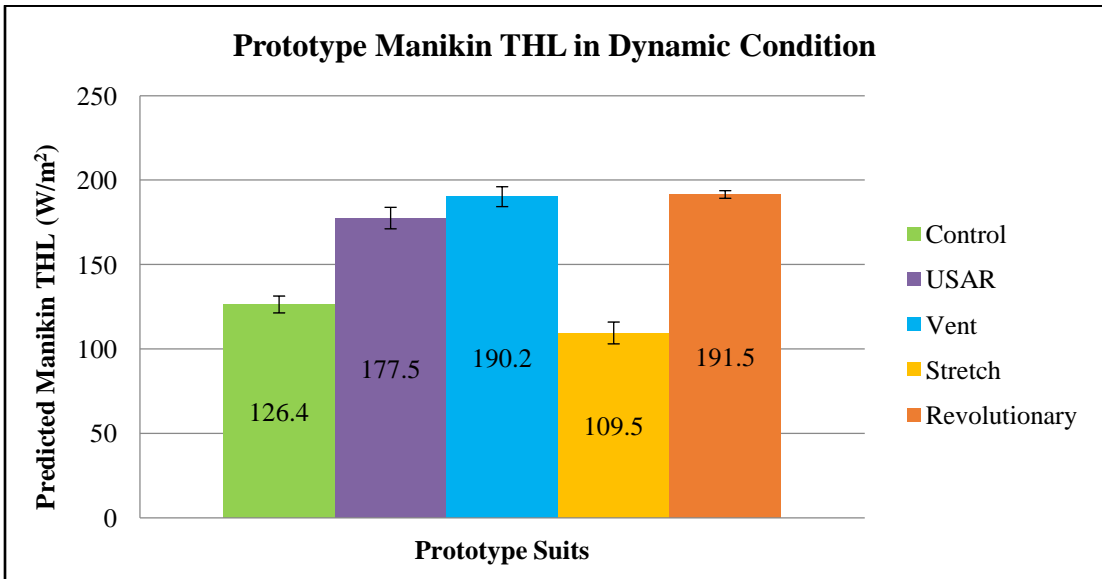


Figure 8-13. Predicted static manikin THL of prototypes in 35°C/35% rh environment.

Manikin THL results in the 35°C/35% RH environment follow similar trends as the 25°C/65% RH environment. The difference is the overall reduction in measured THL in this environment as convective heat loss is not possible under isothermal conditions when skin temperature and air temperature are the same. Instead, the heat loss measured is through sweat evaporation. The USAR, Vent, and Revolutionary prototypes had statistically significant improvements in THL in both test conditions. The USAR had the greatest THL in the static test condition followed by the Revolutionary and Vent prototypes. In the dynamic condition, the Revolutionary prototype had the highest heat loss followed by the Vent and USAR prototypes. The Stretch prototype did not show a statistically significant improvement in THL in either condition. Similar to the previous results, it had a significantly lower THL in the dynamic test condition, compared to the Control. This illustrates the detriment of reducing the air gap volume on wet heat loss as well.

8.4.2 3D Body Scanning

To quantify the reduction in air gap volume, specifically for the Stretch and Revolutionary prototypes, three-dimensional body scanning was conducted. Surface area and volume of the multi-layer garments were measured. The air gap surface area and air gap volume were calculated by subtracting the base layers surface area and volume, respectively. Air gap distance (mm) was calculated according to Equation 7.1. The calculated air gap surface area, volume, and distance (thickness) of each prototype is given in Table 8-6.

Table 8-6. 3D body scanning results of prototypes.

Prototype	Air Gap Surface Area (cm²)	Air Gap Volume (cm³)	Air Gap Distance (mm)
Control	9689.5	83991.7	46.4
USAR	9627.5	71444.6	39.5
Vent	9879.1	98565.4	54.5
Stretch	8638.9	72231.1	39.9
Revolutionary	10454.4	91103.4	50.3

Not surprisingly, the single layer USAR garment had the smallest air gap volume with an air gap thickness of 39.5 mm between the outermost clothing layer and the nude body. A reduction in air gap volume was the main design concept implemented in the Stretch prototype through stretch material panels and a tapered, athletic fit. This prototype had the smallest air gap surface area and second smallest air gap volume and air gap distance. These results quantify the reduction in air gaps implemented through the design modifications in this prototype system. Similar reductions in air gap were not measured in the Revolutionary prototype even though it was a combination of design modifications including the stretch panels. It did not, however, have the tapered pattern for a more athletic fit. In addition, the Revolutionary prototype included active open zipper vents. These vents were measured open, or "activated", when scanned in both the Vent and Revolutionary prototypes. The addition of the stretch panel with the vents lead to the largest air gap surface area because of the way the material draped open (Figure 8-7). The additional volume added to the suit when the vents were open is reflected in the air gap volume results as the Vent prototype had the largest air gap volume and distance (54.5 mm). Increased air gap volume created by vent openings are

not detrimental to heat loss as they allow air and moisture to flow through designed garment openings, dissipating heat from the body to the external environment.

Figure 8-14 illustrates the relationship between air gap distance and dynamic manikin THL. To determine how air gap impacts heat loss, Pearson's correlation coefficients were calculated for static and dynamic manikin THL. These results, along with statistical significance ($p < 0.05$), are presented in Table 8-7.

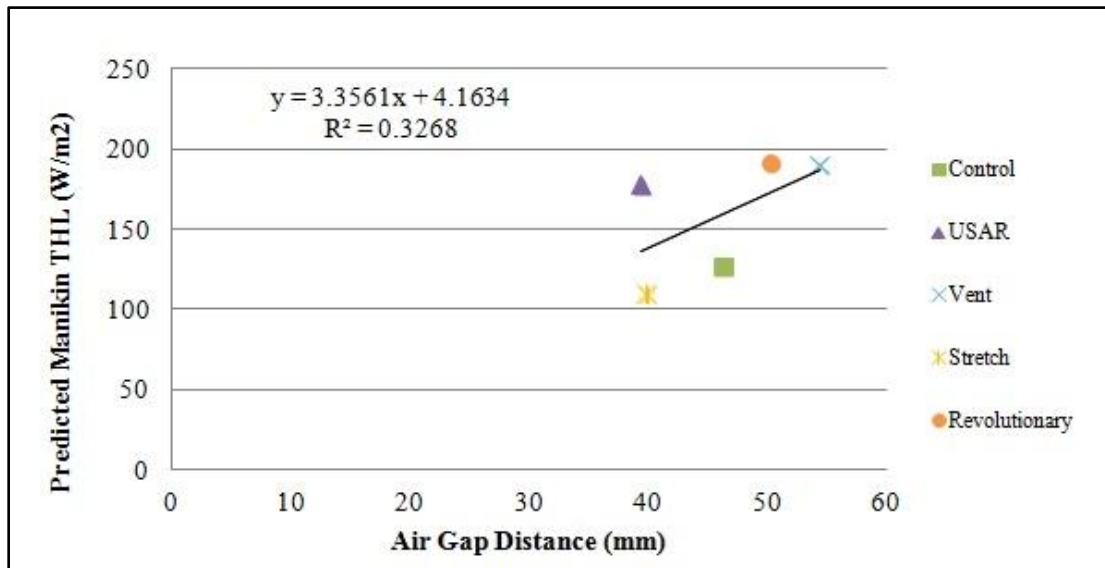


Figure 8-14. Correlation between predicted dynamic manikin THL and air gap distance of turnout prototypes.

Table 8-7. Pearson's correlation coefficients for predicted manikin THL of prototypes.

Measurements	Static THL		Dynamic THL	
	r	p-value	r	p-value
Air Gap Surface Area	0.614	0.27	0.81	0.097
Air Gap Volume	0.296	0.629	0.572	0.314
Air Gap Distance	0.287	0.64	0.565	0.321

Figure 8-14 illustrates the positive relationship ($r = 0.565$) between air gap distance and dynamic manikin THL such that, as air gap distance increases so does heat loss. Based upon literature, however, this principle applies until a certain limit is reached, at which, heat loss is then decreased due to the additional resistance to heat transfer. Further, this relationship was not significant ($p = 0.321$) and only 33% ($r^2 = 0.327$) of the total variation in manikin THL can be explained by the linear relationship between air gap distance and heat loss. Of the relationships examined between air gap and manikin THL, none were statistically significant ($p < 0.05$). The strongest relationship was between air gap surface area and dynamic manikin THL ($r = 0.81$; $p = 0.097$) which was positive indicating that as surface area of the garment increased, so did THL in the walking with wind test condition. Results from this study indicate that as air gap size increases, due to open vents or reduced clothing layers, heat loss through the clothing system significantly increases. These findings substantiate the incorporation of ventilation design modifications and a modular systems approach for structural firefighter turnouts.

8.4.3 Prototype Predicted Physiological Comfort

Virtual human thermal modeling was used as a tool for bridging the gap between THL on a sweating thermal manikin and human wear trial performance measurements. The

raw thermal and evaporative resistance data from the sweating thermal manikin evaluations were input into the RadTherm® software to predict the core temperature (T_{thy}), skin temperature (T_{sk}), and sweat rate (SR) under a specified protocol. Each structural firefighter turnout prototype was modeled according to the human wear trial protocol (Chapter 9) to predict the suit's performance and impact on the wearer's physiological comfort under the same conditions. The overall predicted physiological responses from virtual modeling of the prototypes are shown in Table 8-8 below. The data points given in the table reflect end point, total body average results, at the completion of the 100 minute protocol, following the last five minute rest cycle.

Table 8-8. Overall prototype modeling results.

Condition	Suit	T_{thy} (°C)	T_{sk} (°C)	SR (g/min)
Static	Control	42.12	41.58	30
	USAR	40.69	39.98	30
	Venting	41.16	40.51	30
	Stretch	41.92	41.37	30
	Revolutionary	40.97	40.31	30
Dynamic	Control	39.13	38.06	30
	USAR	38.01	36.3	14.22
	Venting	38.15	36.64	17.07
	Stretch	39.52	38.59	30
	Revolutionary	38.09	36.52	15.93

The body's core temperature must be regulated within a narrow range to maintain homeostasis at 37°C. An increase by just 1°C to 38°C can lead to heat illness symptoms such

as fatigue, cramps, and exhaustion (Teunissen et al., 2012) therefore, a reduction in core temperature of 0.5°C to 1°C, or greater, should have a positive impact on the wearer's comfort. Predicted differences in core temperature (T_{thy}) were greatest between the Control and USAR prototype with a drop of 1.43°C when wearing the single layer outer shell garment and using the static manikin data to predict the results. A similar reduction was found in the dynamic condition but it was not as pronounced, with the USAR prototype having a predicted core temperature 1.12°C lower than the Control. The Revolutionary and Venting prototypes were also predicted to lead to meaningful reductions in the wearer's core temperature in the static and dynamic conditions. The Revolutionary suit was predicted to have a 1.15°C and a 1.04°C reduction in core temperature, compared to the Control, when using the static and dynamic data, respectively. A 0.96°C (static) and 0.98°C (dynamic) drop in predicted T_{thy} was measured for the Venting prototype, compared to the Control turnout.

For the Stretch prototype, the predicted core temperature was less than the Control by only 0.2°C when using the static data. For the dynamic data predictions, the Stretch prototype actually had a higher predicted core temperature than all of the suits, including the Control, at 39.5°C. This poor predicted performance in improving physiological comfort from a heat strain perspective reflects the predicted manikin THL data in the dynamic condition, as well. Improvements in ergonomic function and range of motion were the first priority for the Stretch prototype design as it did not incorporate any direct modifications for heat loss improvement. It does have the potential, however, to reduce metabolic heat production by making it easier for the wearer to move with less restriction. Further testing is necessary on

the human wear level to determine the full impact of the Stretch prototype on both perceived and physiological comfort.

Figure 8-15 illustrates the predicted core body temperature of each suit over the 100 minute protocol using raw thermal insulation and evaporative resistance data from the sweating thermal manikin in the dynamic (walking with wind) test condition. This graph shows the increase in predicted core temperature during the 20 minute work cycles, at five Mets, followed by brief dips, or reductions, due to the five minute rest cycle in between work. Differences between suits become pronounced around 30 minutes into the protocol, five minutes into the second work cycle. Overall results, throughout the 100 minute protocol, demonstrate the Stretch prototype having the highest predicted core temperature of all suits tested, including the Control. This may be due to the reduction in air gap created by the tapered fit and stretch panels which prevents convective and evaporative air flow from occurring. The USAR, Venting, and Revolutionary prototypes maintain steady lower predicted core body temperatures for the wearer's in this particular protocol.

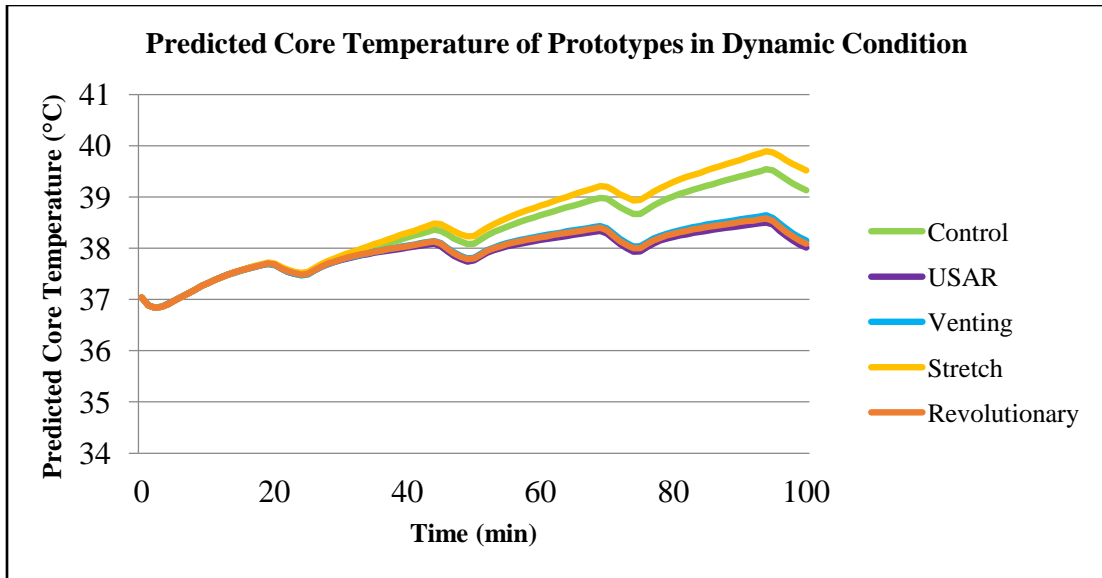


Figure 8-15. Predicted core temperature (T_{thy}) of prototypes using dynamic manikin data.

As discussed in Chapter 4, differences between suits may be more pronounced when examining skin temperature as a parameter for physiological comfort, compared to core temperature. Thermal equilibrium is maintained at a skin temperature of approximately 33°C (Wenger et al., 2001). Skin temperature may fluctuate in a larger range than core temperature as it regulates the wearer's comfort and is affected by environmental conditions (G. Havenith, 1999). Figure 8-16 depicts the average predicted skin temperature for each prototype suit in using the dynamic manikin data. Similar trends were predicted for skin temperature with the Stretch prototype having the highest T_{sk} , followed by the Control, Vent, Revolutionary, and USAR prototypes. The Vent, Revolutionary, and USAR prototypes had similar predicted skin temperatures at the end of the 100 minute protocol (36.3°C-36.6°C) which were much lower than the Control and Stretch prototype (38.1°C-38.6°C).

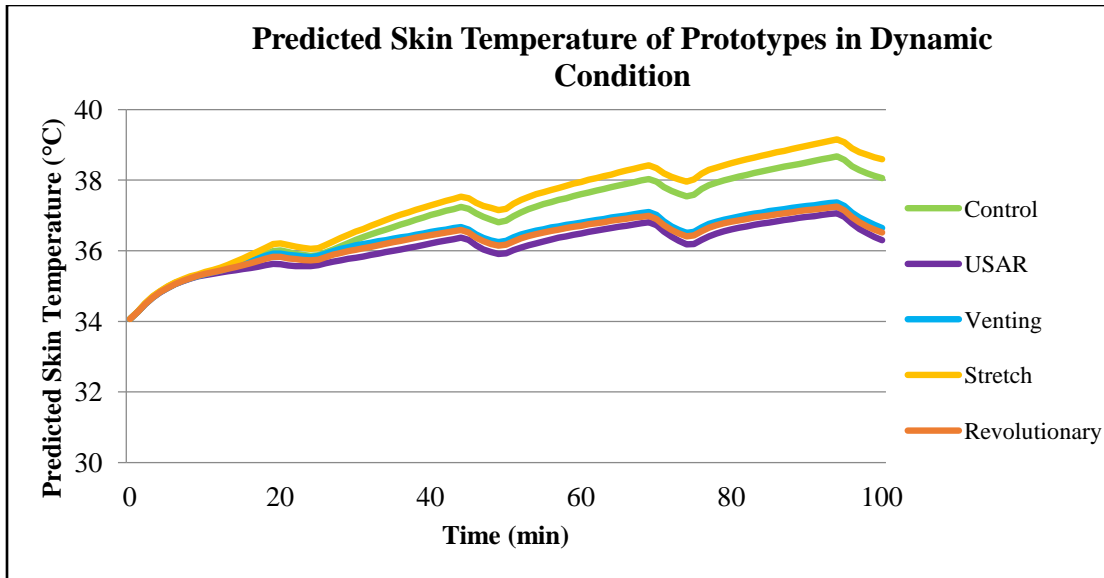


Figure 8-16. Predicted skin temperature (T_{sk}) of prototypes using dynamic manikin data.

Finally, sweat rates were predicted and analyzed for differences between suits. Figure 8-17 illustrates these results. Using the static manikin data, all suits reached the predicted maximum sweat rate of 30 g/min between 40-50 minutes into the protocol. When the dynamic condition data was used to model the predicted physiological responses, only the Control and Stretch prototypes reached the maximum sweat rate. The USAR prototype had the lowest predicted sweat rate, as it was a single layer system, of just 14.2 g/min at the end of the 100 minute protocol. The Venting and Revolutionary prototypes had noteworthy reductions in predicted sweat rate of 17.1 g/min and 15.9 g/min, respectively.

For all three modeled predictive parameters (core temperature, skin temperature, and sweat rate) the USAR, Revolutionary, and Venting prototypes showed improvements in physiological comfort compared to the Control. The Stretch prototype, especially when

modeled using the dynamic condition data, did not show any benefit for physiological comfort. Charts reflecting the modeled physiological responses of the turnout prototypes in the static condition are included in Appendix F.

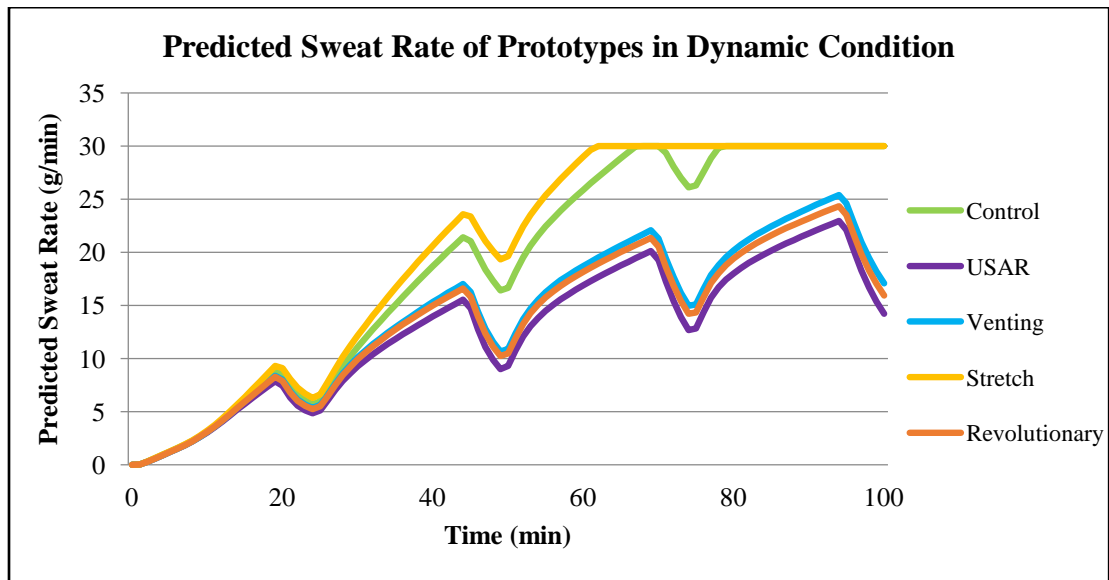


Figure 8-17. Predicted sweat rate (g/min) of prototypes using dynamic manikin data.

8.5 Conclusion

Protective clothing, such as structural firefighter turnouts, serves a functional purpose for the wearer to protect from such hazards as heat and flame, chemicals, and sharp objects. In order to re-design current structural turnouts on the market today for improved comfort and heat loss, without detrimentally sacrificing protection, the functional design process was utilized. The design request was made by the fire service industry and the situation was explored by a team of researchers. Once the problem structure was fully constructed and

understood, specifications were described to create such a turnout with improved comfort performance. From these specifications, important design criteria were established such as increases in manikin THL and meaningful improvements in wearer physiological comfort. Multiple clothing modifications to meet these specifications and design criteria were produced and evaluated. From these results, multiple prototypes were developed and evaluated, as has been discussed in this chapter.

Increases in predicted manikin THL were measured for the USAR, Venting, and Revolutionary prototypes in both test conditions, and in both predicted environmental conditions. The USAR prototype had significantly greater THL performance due to the removal of layers within the clothing system. The addition of active zipper vents along the vertical side seams of the coat and pants contributed to the improvement in heat loss in both the Venting and Revolutionary prototypes. The Stretch prototype, however, did not show a heat loss benefit as it was an ergonomic design focused on improving range of motion and limiting restriction of movement. This suit design may reduce the amount of metabolic heat produced by the body when performing physical tasks such as pulling, crawling, kneeling, climbing, etc. These evaluations will be conducted in a separate ergonomic human wear trial that is outside the scope of this research.

Body scanning results indicate that, to a certain extent, increases in air gap volume actually improve heat loss in multi-layer clothing systems, especially when associated with garment apertures. These air gaps may be larger than the 8-13mm cited in literature (Frackiewicz-Kaczmarek et al., 2014; Spencer-Smith, 1977) without creating a negative impact on heat loss capabilities. In fact, the Stretch prototype with the smallest air gap

distance of the multi-layer prototypes, had the lowest manikin THL. These results confirm those found in Chapter 7, as well.

Finally, predicted physiological responses mirror manikin THL results, in part because they are derived from them. USAR, Venting, and Revolutionary prototypes demonstrate the greatest improvements in comfort, compared to the Control. The Stretch prototype had predicted physiological responses higher than that of the Control, indicating poorer wearer comfort. Further testing is necessary on the human wear level to measure actual physiological responses including heart rate. In addition, subjective evaluations will be conducted to determine the perceived rate of exertion, perceived comfort, and temperature sensation when wearing each turnout prototype and the Control. The details of the human subject wear trial protocol can be found in Chapter 9 and the results in Chapters 10 and 11.

9 Physiological Heat Strain Wear Trial

9.1 Subjects and Test Setup

To determine the relationship between heat loss of a turnout clothing system and the physiological comfort of the wearer, a physiological heat strain wear trial was conducted. Subject qualifications included being a male City of Raleigh or Wake County Fire Department firefighter and having no health concerns that would impede participation in a high heat stress wear trial study. Eight randomly selected City of Raleigh and Wake County Fire Department firefighters between the ages of 25 and 50 met these qualifications and were chosen for this study. All subjects were informed of the protocol and received a copy of the informed consent, both of which were reviewed and approved by the Institutional Review Board (IRB) and the grant funding agency for this project, Federal Emergency Management Agency (FEMA). Subjects participated in six test sessions, with each subject wearing each of the structural firefighter turnout prototypes (Table 8-5) including: the USAR, Venting, Stretch, and Revolutionary, plus the Control and an additional suit that included a novel material innovation. The material innovation suit is outside the scope and research objectives of this study, therefore it is not included in the analysis. Subjects were given at least 48 hours of rest between each test session.

Base layers worn underneath the structural firefighter turnouts included cotton boxer briefs, a standard cotton t-shirt, athletic shorts, and socks. The full ensemble included the donning of base layers, turnout, gloves, helmet, and the subject's own tennis shoes. Because this protocol simulated a vehicle extrication, or scenario where the threat of heat and flame

were not present, the SCBA, thermal hood, and SCBA mask were not worn. Table 9-1 displays the size and average weight of each turnout and the ensemble components.

Table 9-1. Average weight of each component of the ensemble.

Garment	Size	Average Weight (lbs)
Control	42/32; 36L	10.67
USAR	42/32; 36L	6.86
Venting	42/32; 36L	11.99
Stretch	42/32; 36L	10.72
Revolutionary	42/32; 36L	11.53
T-shirt+Shorts	M-XL	0.85
Boxer Briefs + Socks	M-XL; L	0.34
Helmet	adjustable	2.54
Gloves	L	0.93
Tennis Shoes	based on subject	1.49

9.2 Instrumentation

Dependent variables collected from the subjects and used for analysis in this research included intestinal core body temperature, skin temperature, heart rate, and sweat rate. Subjective evaluations were also conducted at specified intervals of the protocol to determine the perceived comfort, perceived exertion, and temperature sensation. Table 9-2 describes the data collected and the devices used to perform the measurements, the sampling time of the data set, and the location on the body from where the measurements were taken.

Table 9-2. Dependent variables, measuring devices, sampling times, and body locations.

Dependent Variable	Device	Sample Time	Location
Intestinal Core Body Temperature	Respironics® core temperature capsule	15 seconds	Intestines
Mean Skin Temperature	Respironics® dermal patches	15 seconds	4 locations (Figure 9-1)
Heart Rate	Polar watch	15 seconds	Belt around chest with watch as a receiver
Heart Rate	EquiVital	15 seconds	Belt around chest
Sweat Rate/Loss	AE Adam GFK; Mettler Toledo Excellence Plus	Before and after exercise	Nude and clothed weight; water weight
Perceived Exertion Rating	Paper Scale	2 min mark and end of every work and rest cycle	Borg 1982 (Appendix G)
Perceived Comfort Scale	Paper Scale	2 min mark and end of every work and rest cycle	ISO 10551, 2001 (Appendix G)
Temperature Sensation Scale	Paper Scale	2 min mark and end of every work and rest cycle	ISO 10551, 1995 (Appendix G)

Intestinal temperature was measured using the Jonah core body temperature capsule pill manufactured by Philips Respironics®, Inc. which was taken by subjects between three and 18 hours prior to each test session. This ensured the capsule was deep in the subject's abdomen by the time the test began. Trials were conducted in the morning, starting at approximately 9:30am, and the afternoon, beginning around 2:30pm. A live feed of intestinal temperature was displayed and recorded using the Equivital software monitoring system. The same system was used to display and record a portion of the heart rate data. Each subject

wore a chest strap with a Sensor Electronic Module (SEM) to collect cardio-respiratory data which was wirelessly transmitted to the same EquiVital software as the Jonah core capsule. A second method for monitoring heart rate was used due to reliability issues with Equivital chest straps in past studies. Polar heart rate monitors, which included chest straps and wrist watch recording devices, were used. EquiVital heart rate monitoring was used as a backup method to the Polar watch in the event it was not activated correctly before exercise began or the recording was accidentally terminated during exercise. Core temperature, skin temperature, and heart rate monitoring were recorded with 15 second interval sampling rates.

Skin temperature (T_{sk}) was measured using four Respironics® dermal patches placed in four separate locations, as specified by the ISO 9886 international standard for calculating mean skin temperature over the surface of the body (ISO, 2004). Locations where skin temperature was measured include: the neck, right scapula, left hand, and right shin, per the ISO standard. These locations are numbers 2, 3, 7, and 12 which are circled in red and shown in Figure 9-1. Mean skin temperature was calculated according to Equation 9.1.

Equation 9.1. Mean skin temperature.

$$T_{sk (mean)} = (T_{sk(2)} * K_2) + (T_{sk(3)} * K_3) + (T_{sk(7)} * K_7) + (T_{sk(12)} * K_{12}); \text{ where:}$$

T_{sk} = mean skin temperature of the body,

$T_{sk(2)}$ = neck skin temperature,

K_2 = 0.28 weighting coefficient,

$T_{sk(3)}$ = right scapula skin temperature,

K_3 = 0.28 weighting coefficient,

$T_{sk(7)}$ = left hand skin temperature,

$K_7 = 0.16$ weighting coefficient,

$T_{sk(12)}$ = right shin skin temperature, and

$K_{12} = 0.28$ weighting coefficient (ISO, 2004).

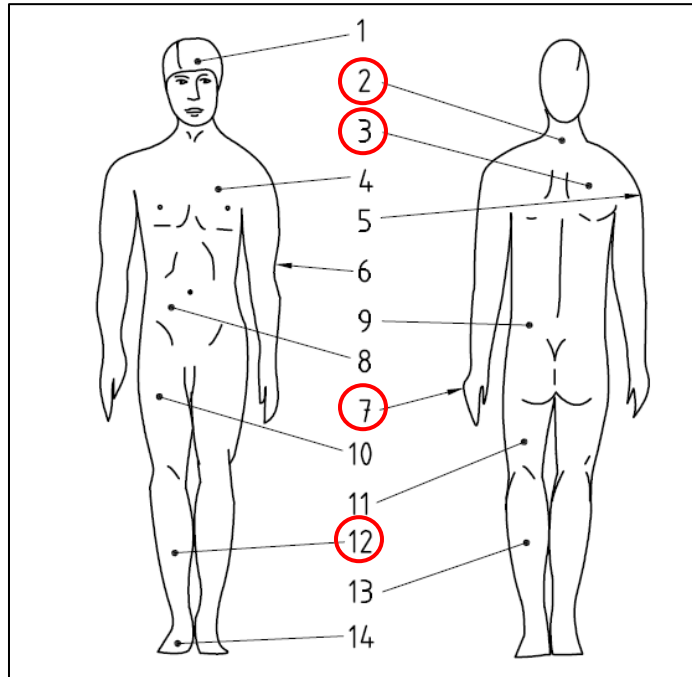


Figure 9-1. Skin temperature patch locations.

Subject body weight, which was required to determine weight loss through sweating, was taken using an AE Adam GFK scale. The scale was calibrated before testing began ensuring it was producing accurate measurements. Weight measurements were taken nude and clothed before and after exercise. Nude weight was taken with the subjects wearing only boxer briefs with instrumentation sensors and clothed weight was taken with the full

ensemble including shorts, t-shirt, socks, turnout, gloves, tennis shoes, and helmet. The weight of each individual ensemble was taken prior to exercise, before the subject dressed, and once the protocol was complete, after the subject doffed the ensemble.

Water weight was also measured in grams for each subject before and after each trial session. Subjects were allowed to consume up to 48 oz of room temperature (35°C) water during each 100 minute protocol test session. The water not consumed was weighed at the end of each session using a Mettler Toledo Excellence Plus scale that had been calibrated prior to use. The consumption of water during the trial was factored into the subject's weight loss.

Ratings from the ISO 10551 Perceived Comfort scale (2001), Borg Perceived Exertion Rating scale (RPE), and the ISO 10551 Temperature Sensation scale (1995) were taken two minutes into the protocol and then at the end of each work and rest cycle (20, 25, 45, 50, 70, 75, 95, and 100 minutes). The perceived comfort scale asks the subject, "How do you perceive your whole body comfort at this moment?" and goes from "0" meaning "Comfortable" to "4" meaning "Extremely uncomfortable" (ISO, 2002). Borg's perceived exertion scale asks the subject, "How do you perceive the exercise at this moment?" and goes from 6 to 20 corresponding to "extremely light" to "extremely hard" perceived exertion, respectively (Borg, 1982; Dorman & Havenith, 2009). Temperature sensation was also collected by asking, "How do you perceive your whole body temperature at this moment?" on a scale from +4, meaning "very hot" to -4, meaning "very cold" (ISO, 1995). The subjective rating scales are included in Appendix G.

9.3 Wear Trial Protocol

Subjects were asked not to consume alcohol 24 hours prior to participation in the study and to drink plenty of water for proper hydration. Core temperature pills were delivered to subjects up to two days prior to the beginning of their individual test sessions. Subjects swallowed a core temperature pill between three and 18 hours prior to beginning the test session. When subjects arrived, they removed their street clothing and changed into boxer briefs, t-shirt, and shorts provided to them. They immediately entered into the habituation room with ambient conditions of 24°C and 50% RH. Subjects remained in this environment for 60 minutes where they were checked and cleared for participation by emergency medical technicians (EMTs) or medical professionals. During the hour long habituation period, subjects were instrumented with dermal skin temperature patches, EquiVital SEM and chest strap, and a Polar SEM, watch, and chest strap. The sensors placed on the subjects did not impact the performance of the subjects during exercise.

Before subjects donned the turnout ensemble, they were asked to use the bathroom and were then weighed in their boxer briefs only with the sensors mentioned above. Subjects were not allowed to drink or eat after this point, except for the five minute rest periods during the exercise protocol, in which they were encouraged to consume up to 12 oz of water, per rest session. The water was heated to 35°C (room temperature in the test chamber) in order to have minimal interference with intestinal core temperature. Once the subjects' post-exercise weight was taken, they were allowed to consume water and food.

Approximately five minutes before the end of the habituation period subjects donned the turnout, tennis shoes, gloves, and helmet. At the completion of the 60 minute period

subjects entered the environmental chamber at the specified climate of 35°C/35% RH. Figure 9-2 illustrates the set up of the environmental chamber. Subjects walked on a treadmill at 3.5 mph at a 3% incline (Figure 9-3) to replicate an approximate 5 met work rate. EMTs remained in the area where they could observe subjects during exercise and could easily access the subjects if necessary. The protocol included four walk/rest cycles where the subjects walked for 20 minutes and then rested sitting (Figure 9-4), with their coat unzipped, for five minutes. During the five minute rest period, it was encouraged that subjects drink up to 12 oz. of water to avoid dehydration. The water was at room temperature in the environmental chamber, at 35°C to avoid as much interference as possible with core temperature measurements.



Figure 9-2. Environmental chamber set up.



Figure 9-3. Wear trial subjects walking on treadmill at 3.5 mph at 3% incline.



Figure 9-4. Subjects sitting at rest with coats unzipped.

During the exercise period three subjective rating scales were given at the two minute mark and at the end of each 20 minute work cycle and each 5 minute rest cycle. Rating scales included perceived exertion, perceived comfort, and temperature sensation. Subjects walked until one of the cut-off criteria was met. The cut-off criteria were strictly enforced and included:

- Reaching the maximum exercise time of 100 minutes.
- Core temperature exceeding 39.5°C, per IRB approval. To ensure the safety of the participants, subjects were removed if their core temperature exceeded 39.2°C.
- Core temperature rise of 0.6°C (1°F) within a five minute period.

- Exceeding 90% of each subject's calculated maximum heart rate (Equation 9.2).
- Other - any other reason exercise was terminated (i.e. subject wants to terminate, interrupted by fire drill, etc.).

The maximum heart rate for each subject was determined using the following equation:

Equation 9.2. Maximum heart rate.

$$\text{Maximum Heart Rate} = 217 - (0.85 * \text{Age}); \text{ where:}$$

Age = current age of each individual subject (Miller & Wallace, 1993).

The maximum heart rate value for each subject was multiplied by 0.9 to determine the cut-off criteria of 90% maximum heart rate. The maximum core temperature allowed in this study was 39.2°C to ensure safety of the subjects and prevent any medical complications.

Upon termination, subjects doffed the entire ensemble, except for their boxer briefs and sensors, thoroughly towed off excess sweat, and were weighed. Subjects sat under supervision of the investigator until a drop in intestinal core temperature was observed. Subjects were given cold water upon exiting the chamber but only drank it within the first 10 minutes if absolutely necessary. During the post-exercise time subjects were checked out by an EMT or medical professional and offered more water, a snack, and a shower. Table 9-3 provides an overview of the test protocol. The test checklist and tabular protocol are included in Appendix H.

Table 9-3. Heat strain wear trial test protocol.

Test Period or Activity	Time (min)	Activity	Garment (s)	Temp - erature °C (°F)	Relative Humidity (%)	Walking Speed (mph)
Habituation	60	Measurements by EMT; Equip with sensors; Sit at rest; Take weight and don test ensemble	Boxer briefs, Shorts, T-Shirt, & Socks	24 (75.2)	50	NA
Exercise	100	3% incline treadmill walk; 20 minutes walk/5 minutes rest; unzip coat and consume water during rest; subjective ratings	Turnout, Tennis shoes, Gloves, & Helmet	35 (95)	35	3.5 mph
Post-Test	~15	Doff ensemble; Towel dry and record weight; Remove sensors; Measurements by EMT; Shower	NA	24 (75.2)	50	NA

9.4 Data Analysis

Core intestinal temperature, skin temperature, and back up heart rate data were downloaded and exported from the SEMs and EquiVital software. The primary heart rate data was downloaded and exported from the Polar devices and online Polar software. The majority of the data reported for this study was recorded in 15 second intervals. Microsoft Excel was used in the event the recording rate deviated from 15 second intervals or data points were missing. Deviations and missing data points were rare and were caused by very

short, temporal losses in data connectivity during the trials. Missing data points within a set of data were calculated with Excel by using interpolation which was appropriate due to only two to three consecutive data points, on average, missing at a time. Microsoft Excel was used to apply the mean skin temperature formula to the data set, as well as for basic statistical analysis. The Physiological Strain Index (PSI) was also calculated using the core temperature and heart rate data. All data was averaged by minute throughout the 100 minute protocol. Minitab, version 16, was used for more advanced methods of statistical analysis including repeated measures ANOVAs, one-way ANOVAs, and two sample t-Tests. Correlations, fitted line plots, regression analyses, and survivability plots were also conducted in Minitab.

10 Physiological Heat Strain of Structural Firefighter Turnout Prototypes with Design Modifications for Improved Comfort

The results and discussion of the human subject physiological wear trial are presented below. Additional analysis correlating the physiological results with the manikin THL and modeled physiological responses is discussed in Chapter 11. All of the subjects' heart rates, core temperatures, and skin temperatures were averaged by minute, throughout the 100 minute protocol, and by suit. This data was plotted over time, along with the rise or change in parameters from each subject's initial start point. PSI was calculated using the core temperature and heart rate data to provide insight into the heat strain experienced by the subjects. The average weight loss per suit is presented along with the average ensemble weight gain. Work time is given by suit and by termination criteria. Finally, subjective evaluations are described and related to each suit's physiological comfort performance.

Regarding average heart rate, core temperature, and mean skin temperature data, sharp increases or decreases in trend lines are due to a subject discontinuing the exercise period. After this point, the respective subject's data is removed from the data set and the remaining subjects' data is represented in the average value throughout the protocol time. The reduction in sample size throughout the protocol is a response in and of itself, however, with each subject removal, the power of statistical significance is reduced. Minitab, version 16, was used to identify significant differences throughout the protocol by conducting repeated measures ANOVAs, One-Way ANOVAs, and individual two-sample t-tests between suits for comparison. A p-value less than 0.05 indicates statistical difference in the parameter between two suits, outside of what may likely occur by chance.

It should be noted that the graphs presented below illustrate the average data for all eight subjects in the study. For statistical analysis purposes, one subject was eliminated due to short work times (did not complete 50% of the protocol exercise time) which were determined to be an outlier.

10.1 Work Time

Average exercise time for each suit is displayed in Table 10-1. Exercise time was not normally distributed as the cut-off criteria of 100 minutes disrupts the normality of the data. The median values are presented to give the average values relevance.

Table 10-1. Average exercise time by suit.

Suit	Average Time (min)	St. Dev.	Range (min)	Median
Control	77	27.5	30-100	89.4
USAR	96	12.1	65-100	100
Venting	87	23.7	32-100	100
Stretch	76	27.2	29-100	87
Revolutionary	90	19.1	54-100	100

Exercise times were reached by each subject exercising until one of the defined cut-off criteria was met (Chapter 9, section 9.3). Subjects were removed from the exercise if 90% of their maximum heart rate was reached, their core temperature exceeded 39.2°C, or their core temperature rose 0.6°C or more within a five minute period. Figure 10-1 illustrates the number of subjects, out of eight total, that reached the maximum exercise time of 100

minutes for each suit. Figure 10-2 depicts the test termination criteria for all 40 trial sessions in the wear study.

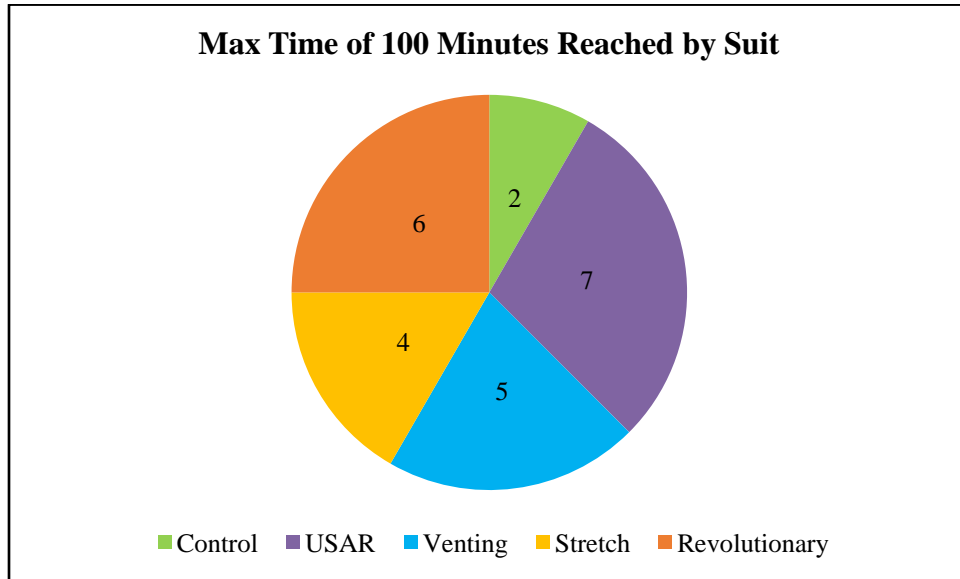


Figure 10-1. Number of subjects that reached the maximum protocol time of 100 minutes by suit.

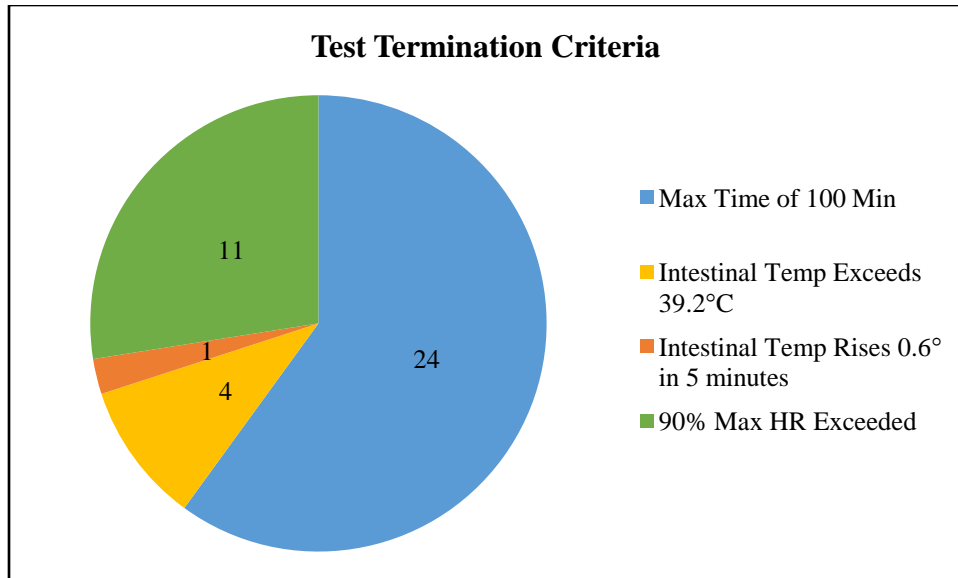


Figure 10-2. Test termination criteria for all trial sessions.

All subjects, except for one, which was removed from the statistical analysis, completed the protocol when wearing the USAR prototype. The majority of subjects also completed the full protocol when wearing the Revolutionary (six subjects) and Venting (five subjects) prototypes. Only two (25%) subjects completed the exercise protocol when wearing the Control turnout. The remaining subjects were pulled from the exercise due to core temperature or heart rate. Work time results illustrate the improvement in physiological comfort as subjects were able to work longer in the prototypes with design modifications for improved comfort compared to a standard turnout.

Of the 40 trial sessions conducted (eight subjects wearing five suits) the majority (24) resulted in subjects completing the maximum exercise time. The majority of subjects pulled were removed due to reaching 90% of their maximum heart rate. Only four instances

occurred where a subject's core temperature exceeded 39.2°C. There was one instance in which a subject's core temperature rose by 0.6°C within a five minute period.

10.2 Heart Rate

In general, heart rate data is sporadic and varies from person to person. The work protocol included four, 20 minute work periods which ended at 20, 45, 70, and 95 minutes, followed by five minute rest periods, which correspond to the dips in all plotted data. The large variation in heart rate, between subjects, is illustrated in Figure 10-3 which displays the raw heart rate data for each individual subject when wearing the Control turnout, along with the suit average.

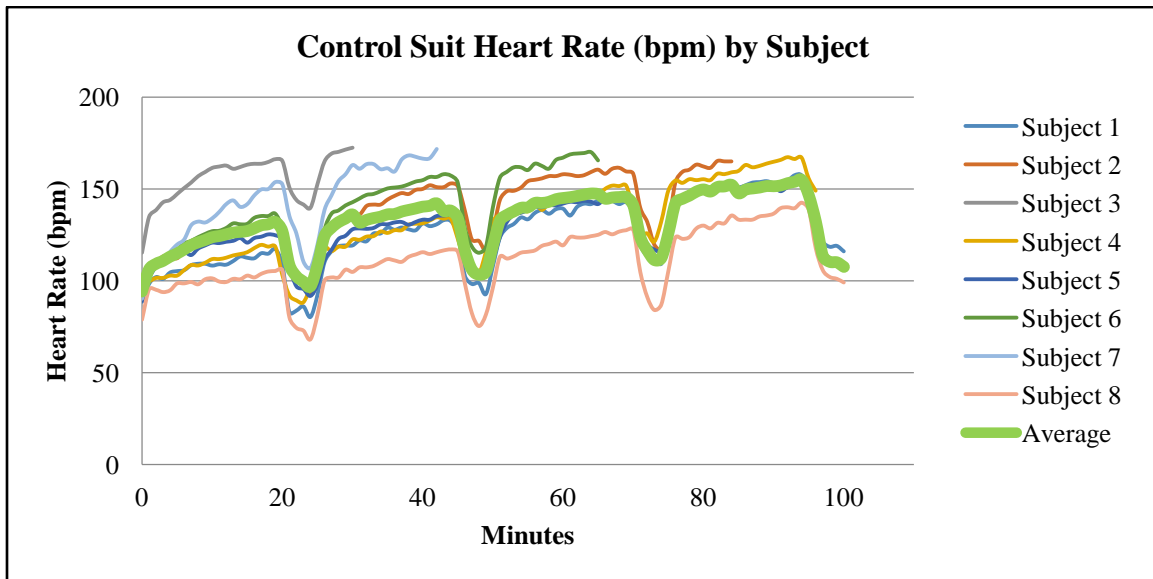


Figure 10-3. Control suit heart rate (bpm) by subject.

Subjects three and seven were discontinued from the exercise prior to 50 minutes into the protocol due to one of the test termination criteria reasons (exceeding 90% of maximum heart rate or core temperature greater than 39.2°C). Only two subjects, out of eight, completed the full 100 minute protocol when wearing the Control turnout. Due to the large variability, all of the heart rate data is presented as average beats per minute (bpm) across all subjects for each suit. Figure 10-4 displays the average heart rate for each suit during the physiological wear trial.

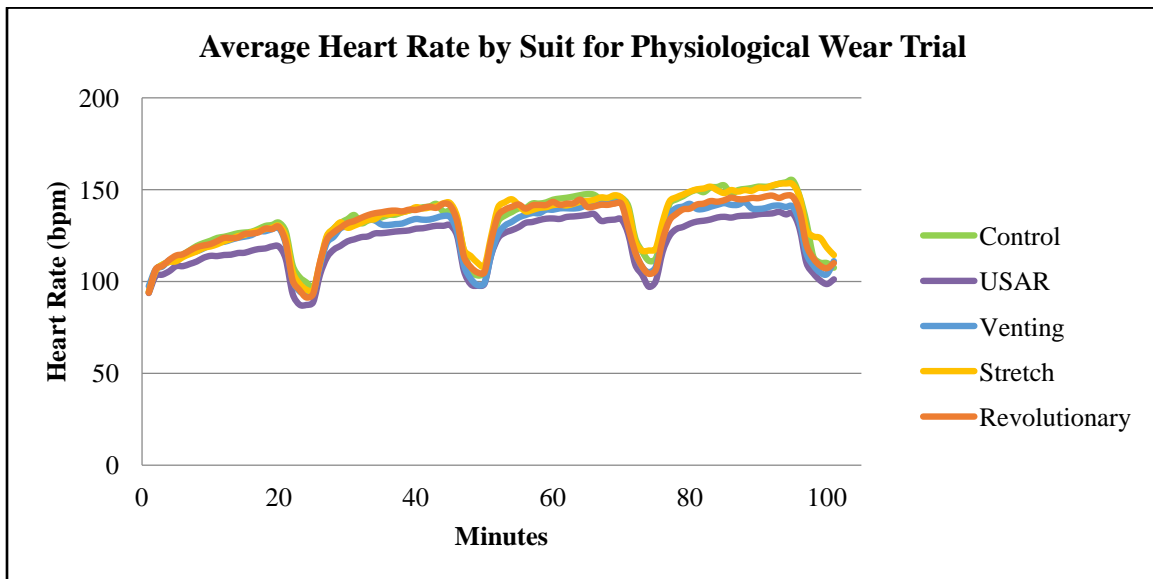


Figure 10-4. Average heart rate for all subjects by suit.

Differences in heart rate between suits are minimal. The most notable difference is between the USAR prototype and the remaining suits as subjects began the protocol with a lower heart rate, on average, and maintained a lower heart rate throughout the protocol.

Differences between suits become more notable as the protocol extends beyond 50 minutes, particularly during the last work cycle (at 95 minutes).

A repeated measures ANOVA was conducted to determine if suit and time were significant predictors and if their interaction was considerable throughout the protocol. P-values of 0.000 indicated that subject and time were significant predictors of heart rate and the interaction between subject and time had a significant effect on heart rate. One-way ANOVAs for the average heart rate data were conducted at 20, 45, 70, 95, and 100 minute intervals to determine when significant differences between suits existed during the trial period. There were no significant differences in heart rate between suits at 20 minutes ($p = 0.471$), 45 minutes ($p = 0.491$), 70 minutes ($p = 0.497$), 95 minutes ($p = 0.329$), or 100 minutes ($p = 0.602$). While the USAR has a lower heart rate throughout the protocol, the difference is not statistically significant.

Figure 10-5 illustrates the change in heart rate over time. The initial heart rate recorded at the beginning of the protocol was subtracted from the subject's heart rate at each minute time interval and plotted.

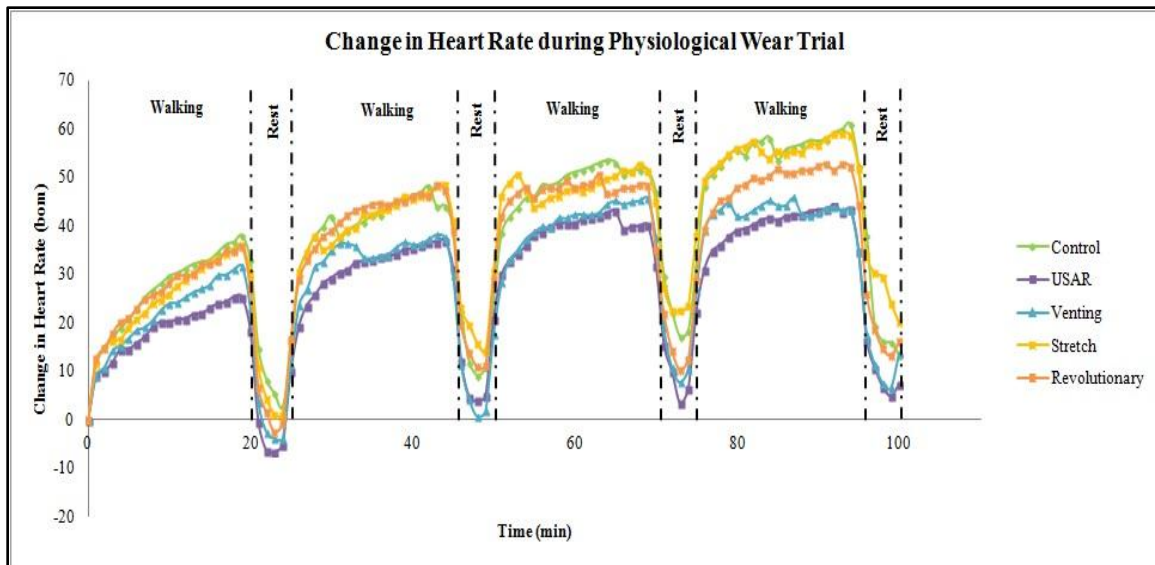


Figure 10-5. Change in heart rate by suit during physiological wear trial.

The change in heart rate data follows a similar trend. However, larger differences exist between suits. The Control and Stretch prototypes have the greatest rise in heart rate, followed by the Revolutionary prototype, and the Venting and USAR prototypes. The two prototypes with the greatest improvements in THL have the lowest rise in heart rate throughout the protocol, comparatively. The USAR and Vent suits had a 20 bpm lower average rise in heart rate compared to the Control after 95 minutes into the protocol

A repeated measures ANOVA indicated ($p = 0.000$) significant interactions between subjects, suits, and time. However, One-Way ANOVAs did not indicate statistically significant differences between the change in heart rate and each suit at the specified time intervals tested (20, 45, 70, 95, and 100 minutes). The p-value at 95 minutes was 0.070 but this was not considered statistically significant at the 95% confidence level. Heart rate data is

generally sporadic and varies more from subject to subject than by suit. This explains the lack of statistical significance between suits even though differences were measured.

10.3 Intestinal Core Temperature

Variability between subjects exists within core temperature data, as well. Therefore, average core temperatures of each suit are presented in Figure 10-6. This graph illustrates smoother trend lines for intestinal core temperature data as the gradual change in temperature differs from the sporadic changes in heart rate.

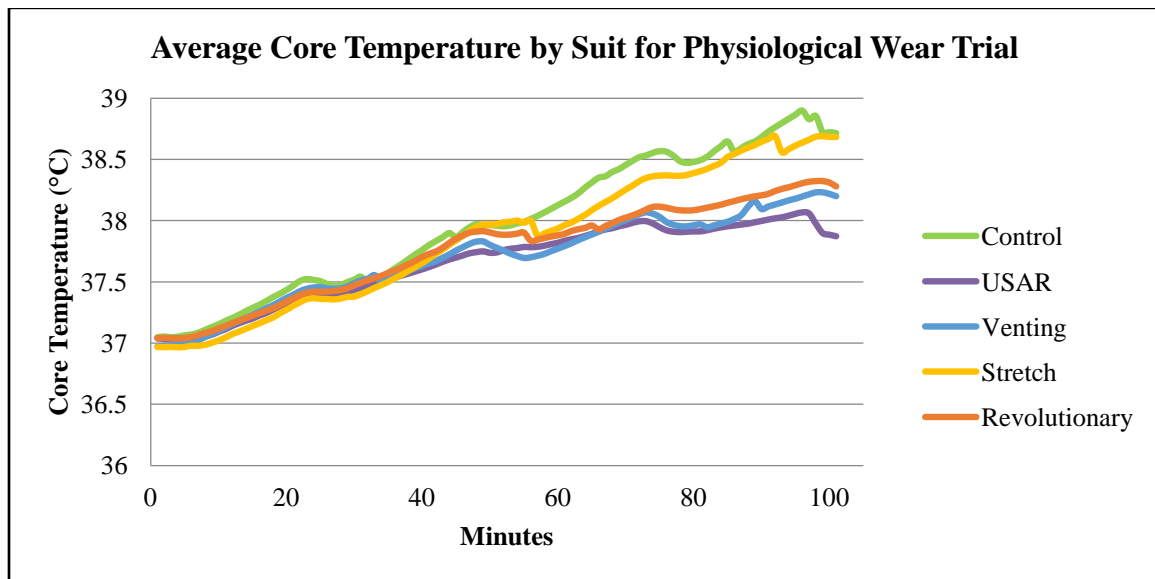


Figure 10-6. Average core temperature for all subjects by suit.

Core temperature differences between suits do not begin to occur until 50 minutes into the protocol. Large, noticeable differences are illustrated around the 70 minute mark with the Control and Stretch prototypes exhibiting much higher core temperatures than the

Revolutionary, Vented, and USAR prototypes. Core temperature data reflects a similar trend as the heart rate measures with the Control and Stretch suits having the highest end point core temperature, followed by the Revolutionary, Venting, and USAR suits.

Repeated measures ANOVA indicated subject, suit, and time were significant predictive factors and the interaction between suit and time were significant. One-Way ANOVAs indicated significant differences between suits at 70 minutes ($p = 0.050$), 95 minutes ($p = 0.014$), and 100 minutes ($p = 0.046$). Two-sample T-tests were conducted between suits at each of the above time intervals. At 70 minutes, the average core temperature was statistically different between the Control and USAR suits ($p = 0.042$) only. At 100 minutes, the Control ($p = 0.009$) and Stretch ($p = 0.003$) turnouts had significantly higher core temperatures than the USAR. P-values for differences between suits at 95 minutes are presented in Table 10-2.

Table 10-2. Statistical data on average core temperature between suits at 95 minutes.

Suit Comparison	P-Value	Suit Comparison	P-Value
Control/USAR	0.005	USAR/Stretch	0.006
Control/Venting	0.037	USAR/Revolutionary	0.266
Control/Stretch	0.186	Venting/Stretch	0.109
Control/Revolutionary	0.027	Venting/Revolutionary	0.695
USAR/Venting	0.621	Stretch/Revolutionary	0.078

At the end of the fourth work cycle (95 minutes), statistical differences between suits are greatest. The core temperature for the USAR, Venting, and Revolutionary prototypes, was significantly lower than the Control at 95 minutes. The USAR suit also had a

significantly lower core temperature than the Stretch prototype. These results are indicative of the trends measured throughout the protocol, as well as, a reflection of the suits' THL performance. There were no significant differences between the manikin THL performance of the Control and the Stretch suits, however, the USAR, Venting, and Revolutionary suits did exhibit significantly higher THL. These improvements in heat loss, through the implementation of reduced clothing system layers and addition of vents, led to significantly lower core temperatures in the subjects tested during the physiological wear trial.

Figure 10-7 illustrates the change in core temperature over time. The initial recorded average core temperature was subtracted from the subject's average core temperature at each minute time interval and plotted.

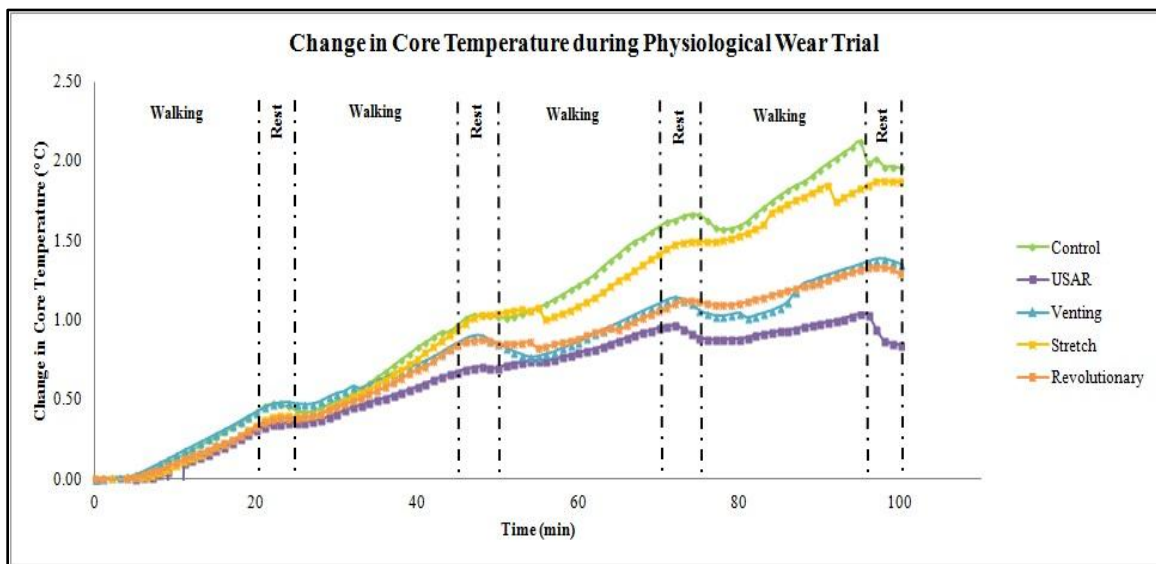


Figure 10-7. Change in average core temperature by suit during physiological wear trial.

The differences in average core temperature rise between suits are more pronounced. The largest rise in core temperature occurred when wearing the Control suit with a maximum rise of 2.12°C at 95 minutes into the protocol, compared to a rise of just 1.04°C when wearing the USAR suit. The Venting and Revolutionary suits led to max rises of 1.38°C and 1.33°C, respectively. By incorporating a modular systems approach during a vehicle extrication scenario, the core temperature rise was reduced by over 1°C throughout the 100 minute protocol. Adding clothing ventilation led to a 0.8°C reduction in core temperature. These decreases in the rise in core temperature are not only statistically significant, according to literature, they are meaningful to the wearer's comfort and practically significant (DenHartog, Walker, & Barker, 2015; Sawka et al., 1992).

A repeated measures ANOVA indicated suit and time were significant predictors and interacted to influence the change in core temperature. One-Way ANOVAs were conducted at the respective time intervals for the end of each work cycle and the protocol end point. Significant differences in the change in core temperature between suits were identified at the end of the third ($p = 0.027$) and fourth ($p = 0.003$) work cycles (70 and 95 minutes), as well as at the end of the protocol ($p = 0.011$), after the last rest period. Individual two-sample T-tests indicated statistically significant differences between the Control suit and the USAR ($p = 0.011$), Venting ($p = 0.034$), and Revolutionary ($p = 0.019$) prototypes at the end of the third work cycle (70 minutes). There was no statistical difference between the Control and the Stretch ($p = 0.387$). At the end of the protocol (100 minutes), the USAR had a significantly lower rise in core temperature compared to the Control ($p = 0.009$) and Stretch ($p = 0.011$) turnouts.

At 95 minutes, differences between suits were most pronounced. Figure 10-8 illustrates a box plot of the change in temperature between suits at the end of the fourth work cycle (95 minutes). Table 10-3 provides the P-values for differences in the rise in core temperature between suits at 95 minutes.

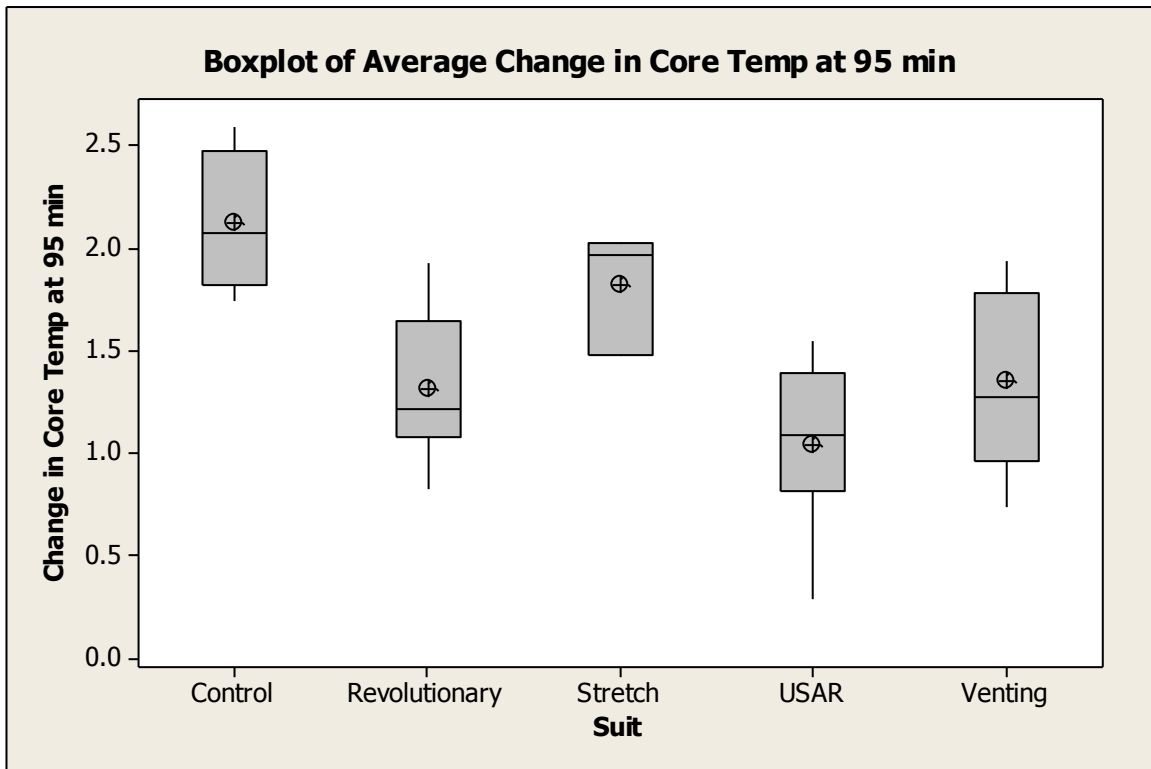


Figure 10-8. Box plot of rise in core temperature at 95 minutes for each suit.

Table 10-3. Statistical data on rise in core temperature between suits at 95 minutes.

Suit Comparison	P-Value	Suit Comparison	P-Value
Control/USAR	0.002	USAR/Stretch	0.020
Control/Venting	0.029	USAR/Revolutionary	0.238
Control/Stretch	0.296	Venting/Stretch	0.139
Control/Revolutionary	0.014	Venting/Revolutionary	0.893
USAR/Venting	0.260	Stretch/Revolutionary	0.082

The significant differences between suits for the rise in core temperature reflect the same differences between suits for the average core temperature. The USAR, Venting, and Revolutionary suits had significantly lower rises in core temperature compared to the Control. The USAR also had a significantly lower rise compared to the Stretch suit. Overall, these results demonstrate the benefits of the design modifications implemented in the turnout prototype suits. These improvements were reflected in the manikin THL results, predicted in the RadTherm® human thermal model, and confirmed by the physiological wear trial. Statistically significant improvements in core temperature are meaningful for the wearer's comfort as variability in core temperature is much smaller than any other parameter measured.

10.4 Physiological Strain Index (PSI)

The Physiological Strain Index (PSI) is a widely accepted, quantifiable, and easy to understand scale for the level of heat strain a person experiences (Moran, Montain, & Pandolf, 1998; Moran, Shitzer, et al., 1998). Thermoregulatory and cardiovascular strain are combined into a scale from 0-10, ranging from no/little strain to very high strain, as shown in

Figure 10-9. The index uses core body temperature and heart rate to calculate the level of heat strain at any given point in time, according to Equation 10.1 below.

Strain	PSI
No to little	0
	1
	2
Low	3
	4
Moderate	5
	6
High	7
	8
Very high	9
	10

Figure 10-9. Physiological Strain Index (PSI).

Equation 10.1. Physiological Heat Strain Index.

$$PSI = 5 * \frac{(T_{ret} - T_{reO})}{(39.5 - T_{reO})} + 5 * \frac{(HR_t - HR_O)}{(180 - HR_O)}, \text{ where:} \quad (10.1)$$

T_{ret} and HR_t = simultaneous measurements taken at the same time point and

T_{reO} and HR_O = initial core body temperature and heart rate values (Moran, Montain, et al., 1998; Moran, Shitzer, et al., 1998; Rubenstein, 2014).

The initial values can apply to any time but in the case of this research, refer to the beginning of the protocol period, and the simultaneous measurements used were the average at each minute during the 100 minute protocol. Figure 10-10 illustrates the average PSI for each suit throughout the protocol, followed by the change in PSI over time in Figure 10-11.

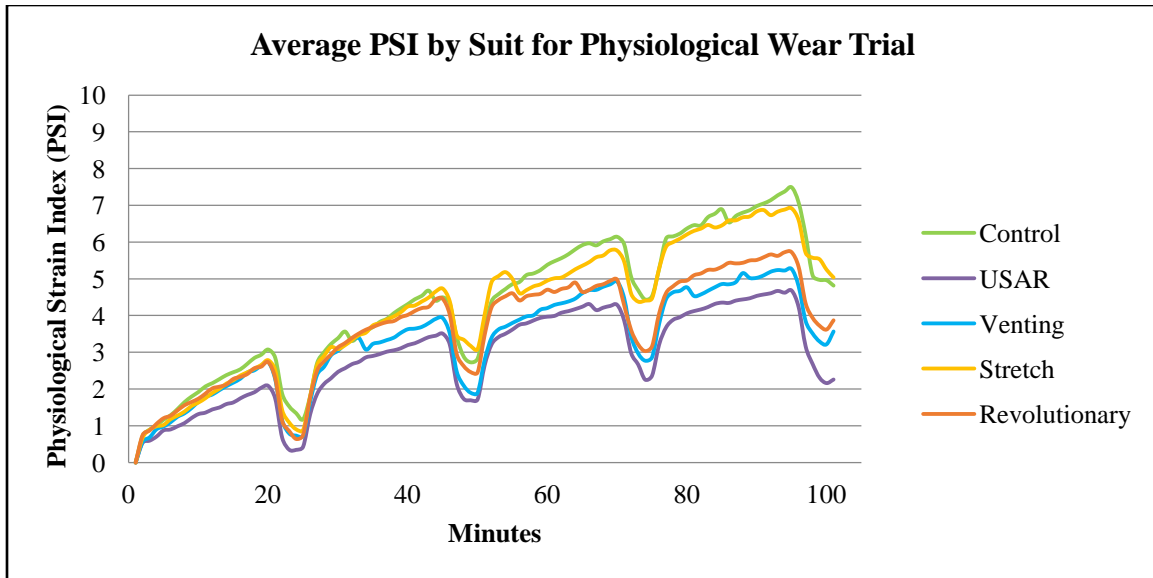


Figure 10-10. Average PSI for all subjects by suit.

As Figure 10-10 illustrates, the maximum PSI values reached in this study ranged from 4.7 for the USAR prototype, to 7.5 for the Control turnout. One-way ANOVAs conducted at the end of each work cycle indicated significant differences between suits at 70 ($p = 0.043$), 95 ($p = 0.017$), and 100 ($p = 0.019$) minutes. Individual two-sample T-tests showed the USAR (3.9 PSI) and Revolutionary (4.3 PSI) prototypes had significantly lower PSI values than the Control (5.9 PSI) at the end of the third work cycle (70 minutes). The USAR prototype had a lower rating on the scale at "low strain", compared to the Stretch, with an average heat strain rating of "moderate". The difference between these two suits was also statistically significant ($p = 0.027$) at 70 minutes.

By the end of the 100 minute protocol, the USAR and Venting prototypes both exhibited, on average, significantly lower levels of heat strain when compared to the Stretch

prototype. The USAR suit was also significantly different ($p = 0.035$) from the Control suit. Greatest differences in heat strain between suits were exhibited at the end of the fourth work cycle, or 95 minutes. The USAR, Venting, and Revolutionary prototypes all exhibited significantly lower levels of heat strain compared to the Control at this time point. Table 10-4 gives the statistical significance between suits for PSI at 95 minutes.

Table 10-4. Statistical data on PSI of suits at 95 minutes.

Suit Comparison	P-Value	Suit Comparison	P-Value
Control/USAR	0.003	USAR/Stretch	0.006
Control/Venting	0.035	USAR/Revolutionary	0.199
Control/Stretch	0.321	Venting/Stretch	0.069
Control/Revolutionary	0.035	Venting/Revolutionary	0.568
USAR/Venting	0.550	Stretch/Revolutionary	0.077

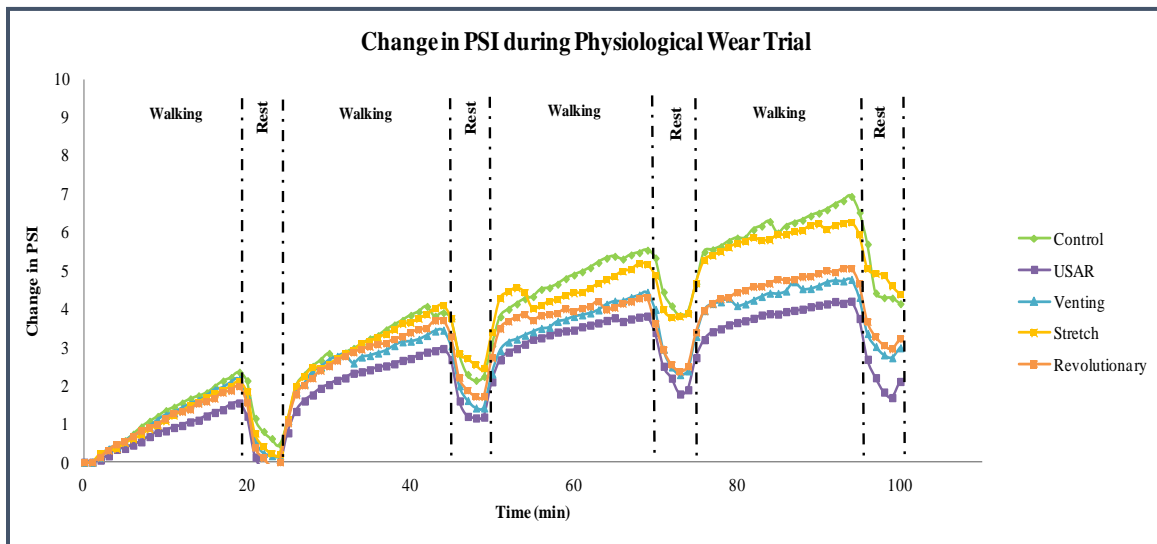


Figure 10-11. Change in PSI by suit over wear trial protocol.

Figure 10-11 illustrates the average rise, or change, in PSI for each suit over the 100 minute protocol. There were no significant differences in the rise in physiological strain between suits until the end of the third work cycle (70 minutes) ($p = 0.04$) as indicated by a one-way ANOVA. At 70 minutes, subjects wearing the USAR and Revolutionary prototypes experienced significantly lower levels of increased strain when compared to both the standard Control firefighter turnout and the Stretch prototype. At the end of the 100 minute protocol, the only significant difference in the rise in physiological strain between suits was between the USAR and Stretch prototypes with increases in PSI of 2.1 and 4.4, respectively. At the end of the fourth work cycle, 95 minutes, is where the greatest differences in increase in physiological strain were identified. Similar to trends found in the core temperature data, at 95 minutes, the USAR, Venting, and Revolutionary prototypes all had significantly lower rises in PSI when compared to the Control turnout. In addition, the USAR also performed significantly better than the Stretch prototype.

PSI differences between prototypes ranged from "low" strain for the USAR, Venting, and Revolutionary prototypes to "moderate" strain for the Control and Stretch turnouts. Statistical analysis determined these differences to be significant at the end of the third and fourth work cycles (70 and 95 minutes) demonstrating the improved physiological comfort performance of the design modifications incorporated into these prototypes. PSI will be further analyzed in Chapter 11 to aide in establishing a benchmark for manikin THL as it relates to physiological comfort.

10.5 Skin Temperature

Skin temperature readings were taken from four locations (back of the neck, back right shoulder, left hand, and right shin) and the overall mean skin temperature was calculated according to ISO 9886 (see Chapter 9, section 9.2). The mean skin temperature of each subject was averaged together with all other subjects for each suit to obtain the average mean skin temperature and the average change in mean skin temperature. Figure 10-12 illustrates the mean skin temperature average for each suit. Average skin temperature data plotted for each individual location can be found in Appendix I.

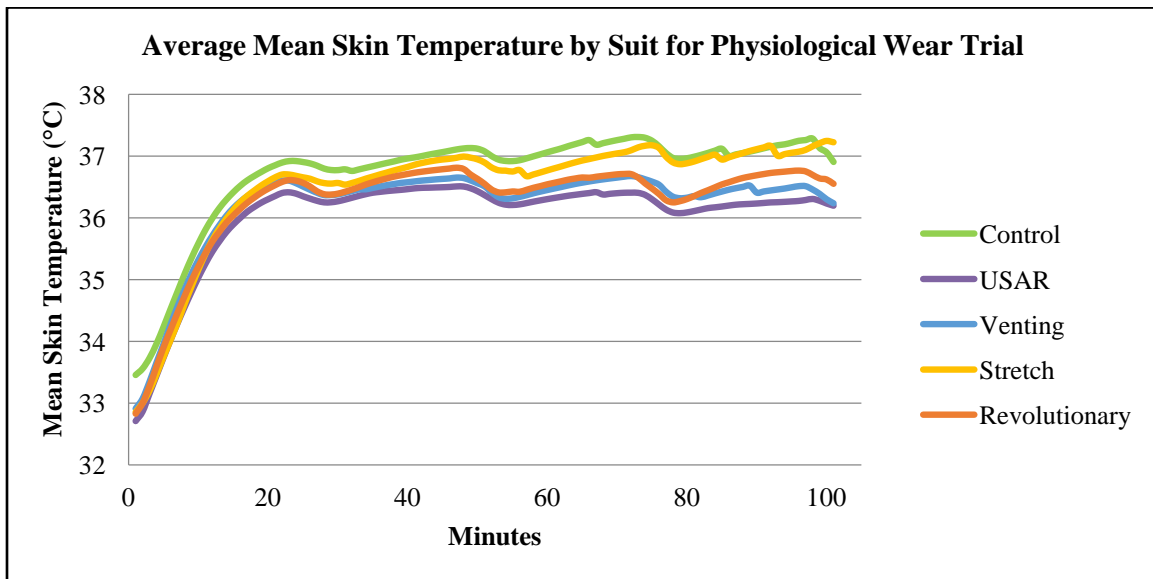


Figure 10-12. Average skin temperature for all subjects by suit.

Differences in skin temperature between suits are less pronounced as variation is greater and the fluctuation range of skin temperature is also wider. Differences between suits

are not noticeable until the 45 minute mark, at the end of the second work cycle. These differences between suits are statistically significant at the end of the second ($p = 0.028$), third ($p = 0.004$), and fourth ($p = 0.001$) work cycles (45, 70, and 95 minutes), as well as at the completion of the work protocol (100 minutes) ($p = 0.001$). Individual two-sample T-tests were conducted between suits at each time interval where significant differences were identified.

At 45 minutes, the only significant differences were between the USAR prototype, which had a significantly lower mean skin temperature than the Control ($p = 0.024$) and Stretch ($p = 0.002$) turnouts. At the end of the third work cycle (70 minutes) the USAR and Venting prototypes both had significantly lower skin temperature than the Control ($p < 0.05$). At the end of the entire work protocol (100 minutes), differences in skin temperature between suits were even more pronounced, but when compared to the Stretch prototype, not the Control. The USAR and Control turnouts did not have significantly different skin temperatures at the end of the protocol, after the last rest period. However, the skin temperature of the subjects wearing the Stretch prototype, continued to rise. The USAR ($p = 0.002$), Venting ($p = 0.004$), and Revolutionary ($p = 0.014$) prototypes all had significantly lower skin temperature than the Stretch prototype which retained more heat than any of the turnouts evaluated. In addition, the USAR suit (36.12°C) had significantly lower ($p = 0.041$) skin temperature than the Revolutionary suit (36.56°C) at the end of the protocol (100 minutes). The most pronounced differences between suits occurred at 95 minutes for participants still involved in the protocol at the end of the fourth work cycle (95 minutes). Table 10-5 gives the P-value comparisons between suits at this time interval.

Table 10-5. Statistical data on average skin temperature between suits at 95 minutes.

Suit Comparison	P-Value	Suit Comparison	P-Value
Control/USAR	0.000	USAR/Stretch	0.011
Control/Venting	0.006	USAR/Revolutionary	0.026
Control/Stretch	0.406	Venting/Stretch	0.043
Control/Revolutionary	0.025	Venting/Revolutionary	0.231
USAR/Venting	0.262	Stretch/Revolutionary	0.184

When comparing prototype suits to the Control, skin temperature results were similar to those of core temperature and PSI. The USAR, Venting, and Revolutionary prototype suits all had significantly lower mean skin temperatures at the end of the last work cycle (95 minutes), compared to the traditional turnout found on the market today. Differences between suits, other than the Control, however, were evident when analyzing skin temperature data. Not only did the USAR prototype have significantly lower mean skin temperature than the Stretch prototype, but the Venting suit did, as well. In addition, the USAR suit, with its single outer shell layer outperformed the Revolutionary suit with its Venting plus Stretch combination. While the Revolutionary prototype had significantly lower skin temperature when compared to the Control, it was not significant when compared to the Stretch. Although the Revolutionary suit contains the benefits of clothing ventilation, it is hindered by its incorporation of the stretch panels which have lower THL on the fabric and garment level. Therefore, it can be concluded that clothing ventilation, in this case, provides greater comfort performance than when combined with the stretch panels in the Revolutionary prototype.

The change in skin temperature, over time, was also analyzed as it was with the heart rate, core temperature, and PSI data. Figure 10-13 illustrates the average rise in skin temperature for all subjects, by suit.

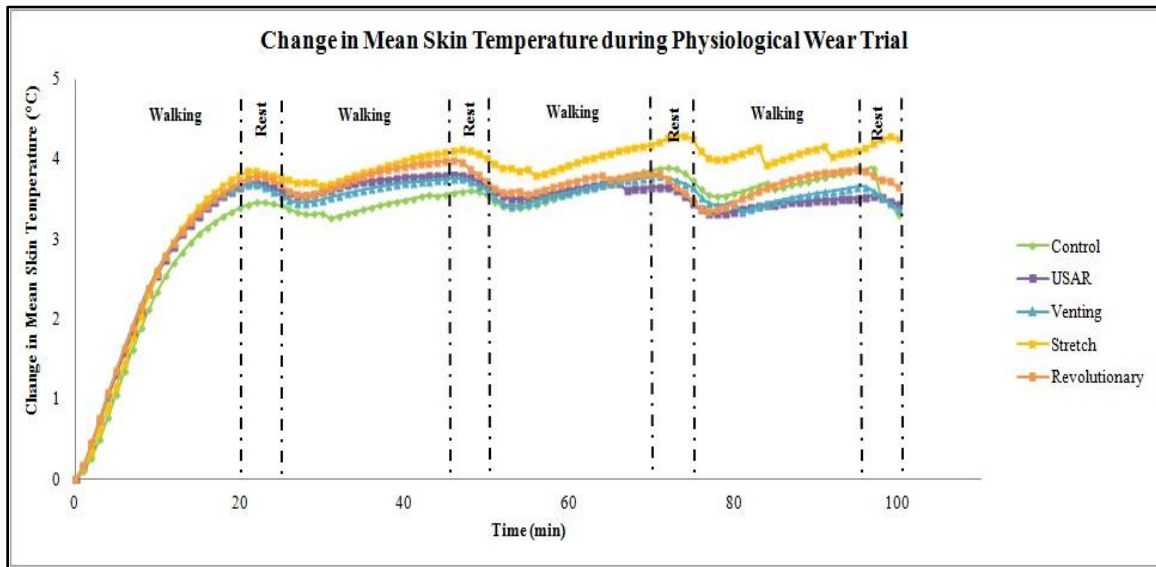


Figure 10-13. Change in skin temperature by suit during physiological wear trial.

The rise in skin temperature was similar for all suits during the first 50 minutes of the protocol, except for the Control suit which had a lower average change in skin temperature due to its higher skin temperature at the start of the protocol. This reflects why it is important to look at overall averages and not just change over time. The Stretch prototype had the largest rise in skin temperature from the beginning of the protocol to the end. A repeated measures ANOVA did not identify significant interactions between the factors of suit and time ($p = 0.081$). However, One-Way ANOVAs were conducted at the 20, 45, 70, 95, and

100 minute intervals for the average change in skin temperature by suit. Individual ANOVAs at each time interval confirmed the repeated measures ANOVA result that no statistically significant differences between suits occurred for the rise in skin temperature over time. The higher start temperature for the Control, along with only two subjects finishing the full protocol, most likely contributes to the lack of statistical differences between suits for rise in mean skin temperature.

10.6 Weight Loss

The weight of the ensemble, including the turnout, underwear, shorts, t-shirt, socks, helmet, gloves, and tennis shoes was taken before and after each wear trial session. The nude weight, including underwear, polar watch, polar heart rate strap, Equivital strap, and skin temperature patches, was taken before and after each session, as well. The average total weight loss of the subjects, for each suit, considering water intake, is shown in Figure 10-14. The average weight gain for each turnout ensemble is illustrated in Figure 10-15.

The average human subject weight loss reflects the amount of sweat lost from the body of each subject. Weight loss by suit ranged from 1381 grams for the Stretch prototype to 1560 grams for the Revolutionary prototype. The Stretch prototype had the lowest weight loss which could be due to its high evaporative resistance, trapping sweat on the body. This would directly impact the wearer's comfort as literature demonstrates that acclimatized humans, such as the firefighter subjects in this study, sweat more during heat stress, and this additional sweat is perceived as comfortable as it provides a pleasant cooling sensation to the skin, however, only if effectively evaporated (Cabanac, 1981; Gonzalez, Pandolf, & Gagge, 1973). The higher weight loss in the Revolutionary suit could be due to the stretch

component panels which had lower THL than the base composite. These low THL fabric panels and additional fabric weight may have generated even more sweat but it was easily evaporated through the incorporation of the open vents in the Revolutionary prototype design. Overall, little differences are measured due to all subjects being close to the maximum sweat rate. While subjects were mostly thermal neutral during the first work/rest cycle, they experienced high levels of perspiration for 75% of the protocol, including the rest cycles.



Figure 10-14. Average human subject weight loss by suit.

The two suits which had the lowest heart rate, core temperature, and skin temperature, also had the lowest ensemble weight gain. The USAR and Vented prototypes were less cumbersome on the wearer and allowed for work to be completed for longer amounts of time

before the onset of heat stress occurred. An explanation for the high ensemble weight gain (608 grams) when wearing the Stretch suit could be the high evaporative resistance and absorbency of the stretch component materials, however fabric absorbency was not evaluated within the scope of this research. In addition, this suit was the most cumbersome leading to the highest heart rate and mean skin temperature of all suits in the study.

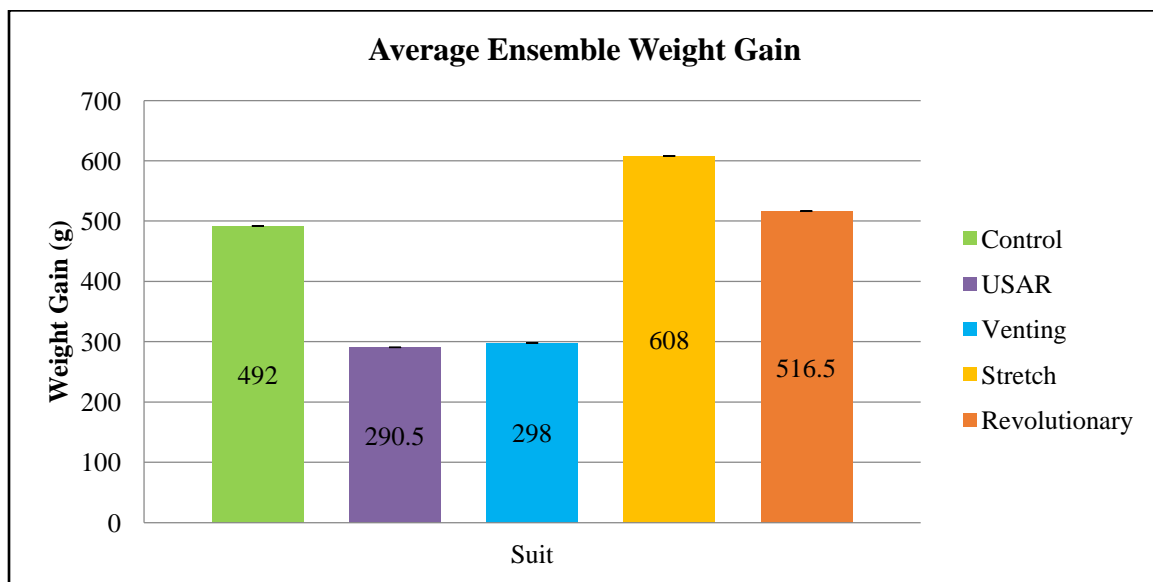


Figure 10-15. Average ensemble weight gain by suit.

One-Way ANOVAs indicated there were no statistically significant differences between suits for weight loss ($p = 0.686$) or for ensemble weight gain ($p = 0.183$). Weight loss was correlated with turnout weight, as previous literature has shown that as ensemble weight increases, human subject weight loss increases also (Walker, 2013). However, the correlation in this study was extremely weak with a Pearson's correlation coefficient of $r =$

0.131. Therefore, other factors such as the reduction in clothing insulation and isolated ventilation which exposed the subject's skin directly to the external environment, played a larger role in sweat loss in this research. While the Venting and Revolutionary prototypes weighed the most at 5.44 kg and 5.23 kg, respectively, the weight loss between the two suits differed by 150 grams. The lack of significant differences in weight loss and ensemble weight gain may be attributed to the consistent use of the same fabric composite in all suits, with the exception of the stretch component panels in the Stretch and Revolutionary suits. Overall, the weight of the turnouts were consistent (Table 9.1) and did not vary widely from prototype to prototype except for the USAR which was four to five pounds lighter.

10.7 Subjective Evaluations

Subjects were asked to give a rating for their perceived comfort, perceived exertion, and temperature sensation at two minutes into the protocol and at the end of each work (20, 45, 70, and 95 minutes) and rest (25, 50, 75, and 100 minutes) cycle. Figures 10-16, 10-17, and 10-18 illustrate the overall average rating for each suit, for the entire work protocol, for each of the rating scales.

Average perceived comfort was evaluated using the ISO 10551 scale from 0, meaning "comfortable", to 4, meaning "extremely uncomfortable." Average ratings for the suits in this study ranged from 0.8 for the USAR prototype to 1.1 for the Stretch prototype. Overall, subjects did not indicate they were more than slightly uncomfortable (a rating of 1) in any of the suits. Differences in perceived comfort between suits were not large. Two-sample T-tests did not indicate significant differences between suits for average perceived comfort ratings.

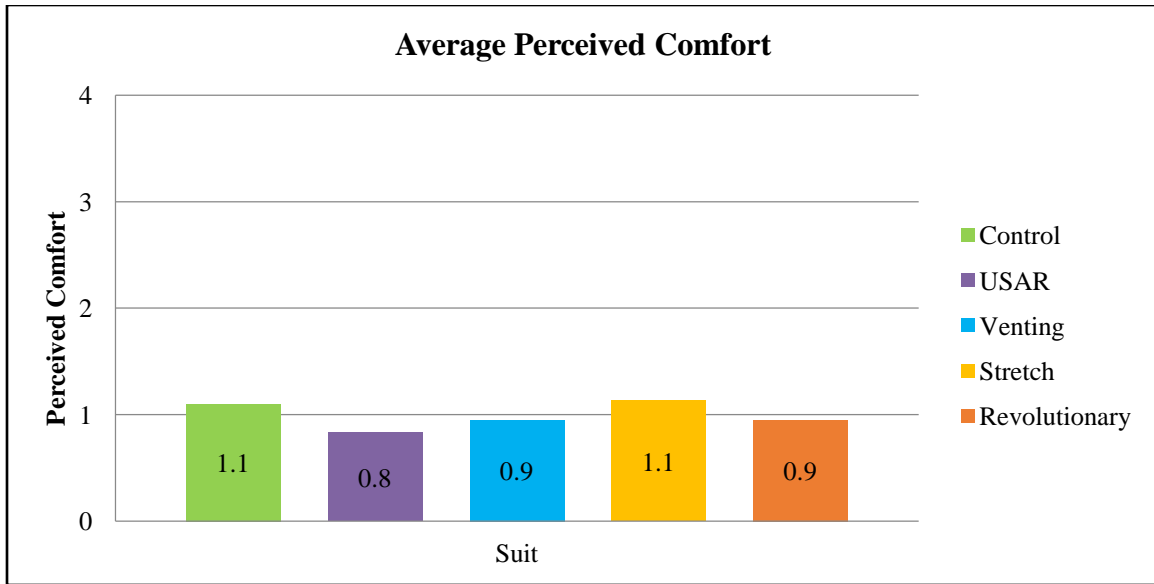


Figure 10-16. Average perceived comfort rating by suit.

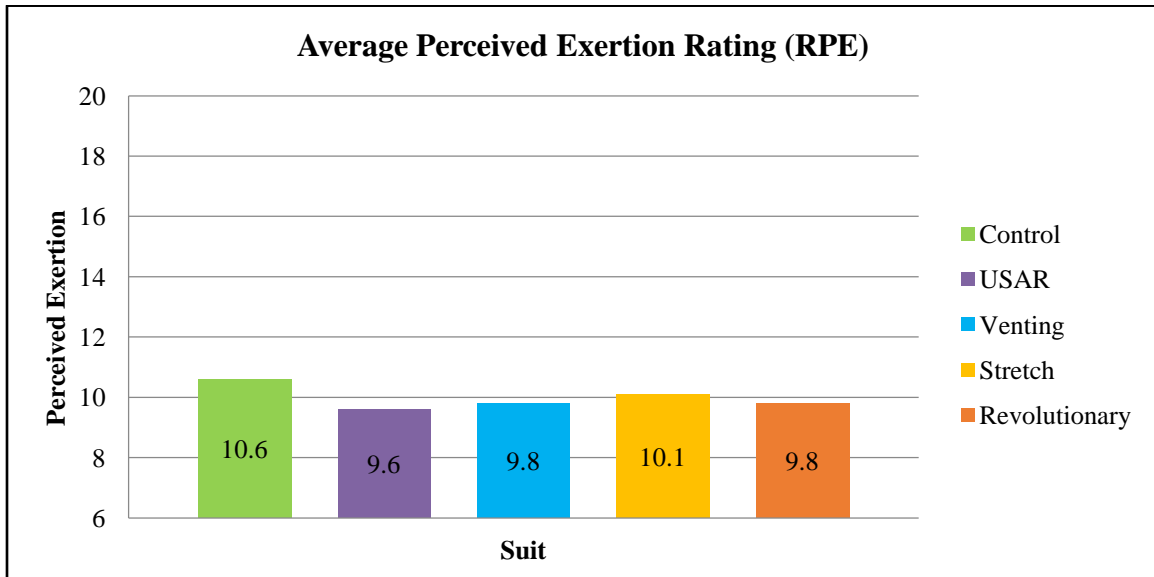


Figure 10-17. Average perceived exertion rating by suit.

Perceived exertion was rated on a scale from six to 20 with text choices ranging from "extremely light" to "extremely hard" at odd numbers (7, 9, 11, 13, 15, 17, and 19) only. Differences between suits were even smaller for perceived exertion which ranged from 9.6 for the USAR prototype to 10.6 for the Control turnout. These ratings correspond to "very light" and "light" perceived exertion. There were no statistically significant differences between suits for the overall average perceived exertion ratings.

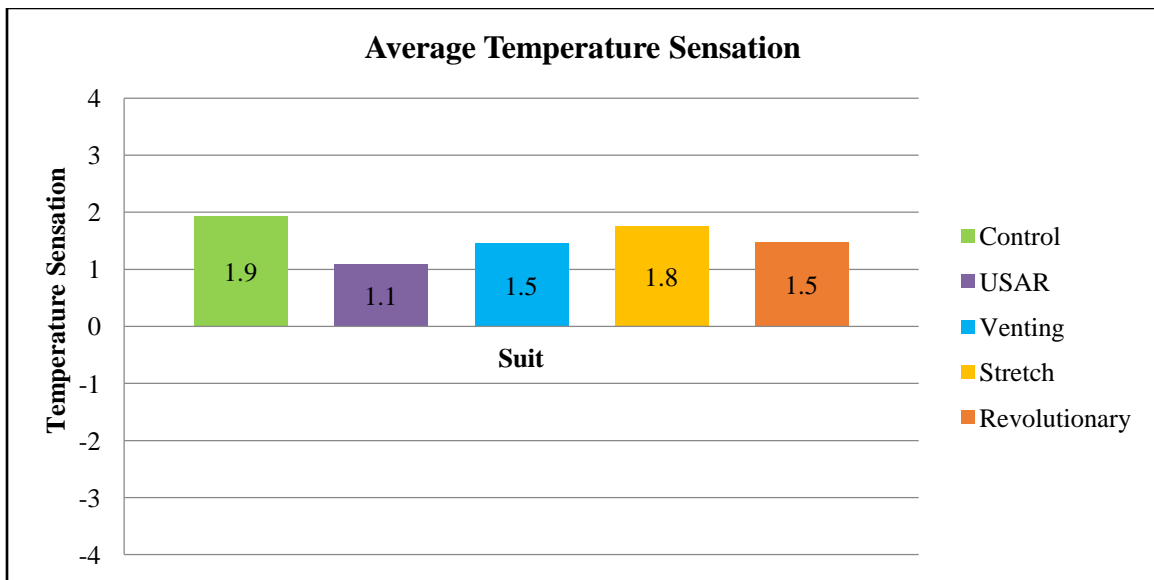


Figure 10-18. Average temperature sensation rating by suit.

Temperature sensation is a rating scale which assesses the subject's perceived whole body temperature. It is evaluated on a scale from -4 (very cold) to +4 (very hot). Differences between suits were slightly more pronounced for this rating. The USAR prototype had the coolest temperature sensation average at +1.1 which corresponds to "slightly warm." The

Venting and Revolutionary suits had similar ratings at 1.5. The Stretch prototype had a higher rating of 1.8. The Revolutionary prototype is a combination of the Stretch and Venting. This suit's lower temperature sensation rating illustrates the ability of clothing ventilation to cool the body and it be perceived by the wearer. The Control had the highest rating at 1.9, close to +2 which corresponds to "warm". At 95 minutes into the protocol, the Control and Stretch suits both received ratings of +4 by at least one subject.

Statistical analysis demonstrated a significantly lower ($p = 0.02$) temperature sensation rating for the USAR suit when compared to the Control turnout, for the overall average. One-Way ANOVAs were conducted at the end of each work cycle interval (20, 45, 70, and 95 minutes) to determine if statistically significant differences were present. Significance was determined at the end of the third ($p = 0.005$) work cycle (70 minutes) and individual two-sample T-tests were conducted to identify differences between suits for thermal sensation. At 70 minutes, the USAR and Venting suits both demonstrated significantly cooler temperature sensations than the Control and Stretch suits ($p < 0.05$).

10.8 Discussion and Conclusion

Overall results from the physiological heat strain wear trial demonstrate the improved comfort performance of the USAR, Venting, and Revolutionary prototype turnouts. Work time is a response in and of itself with over half of all trial sessions ending with subjects completing the maximum exercise time for the 100 minute protocol. The majority of instances in which subjects were pulled was due to reaching 90% of their maximum heart rate (Figure 10-2). Of the four instances in which subjects were pulled due to reaching their maximum core temperature, three occurred when wearing the Control turnout and one

occurred when wearing the Stretch prototype. All subjects, except one which was determined to be an outlier, completed the full protocol when wearing the USAR prototype, compared to six when wearing the Revolutionary suit, five when wearing the Venting, four when wearing the Stretch, and only two subjects when wearing the Control turnout (Figure 10-1). Shorter work times illustrate the quicker onset of heat stress when wearing the Control and Stretch suits as subjects were pulled sooner due to high heart rate or core temperature.

Differences between suits for the average heart rate data were distinctive but were not found to be statistically significant. When analyzing the change, or rise, in heart rate over time, differences between suits were even more pronounced. However, due to the large variability between subjects and sporadic nature of heart rate, these differences were not significant.

Intestinal core temperature data directly indicates the heat strain experienced by the wearer. Heat strain occurs when the body can no longer regulate core temperature at the necessary level (Moran, Shitzer, et al., 1998). For healthy subjects, the body's thermostat for intestinal core temperature is set around 37°C (Cabanac, 1981). Heat exhaustion, however, begins to occur between 38°C and 40°C. Participants in the study were removed from exercise before being allowed to reach a core temperature greater than 39.2°C.

In this research study, the modular approach turnout made up of a single layer, outer shell had a significantly lower core temperature than the Control and Stretch prototype after 70 minutes into the protocol. By the end of the last work cycle (95 minutes), the USAR, Venting, and Revolutionary prototypes all had significantly lower core temperatures than the Control, indicating a significant improvement in human thermal comfort for the modified

turnouts. Decreases in the rise of core temperature by 0.8°C to 1°C are not only statistically significant, for the Venting and USAR suits, respectively, but they are meaningful for the wearer's physiological comfort.

Similar trends were found when analyzing the PSI data. Differences between suits were not significant until the end of the third work cycle (70 minutes). Subjects wearing the USAR, Venting, and Revolutionary prototypes exhibited significantly lower levels of physiological strain at 70 and 95 minutes (Figure 10-19). The same was true for the change in PSI over time, as strain increased during the exercise protocol. The PSI ratings ranged from "low" for the USAR, Venting, and Revolutionary prototypes to "moderate" for the Control and Stretch turnouts.

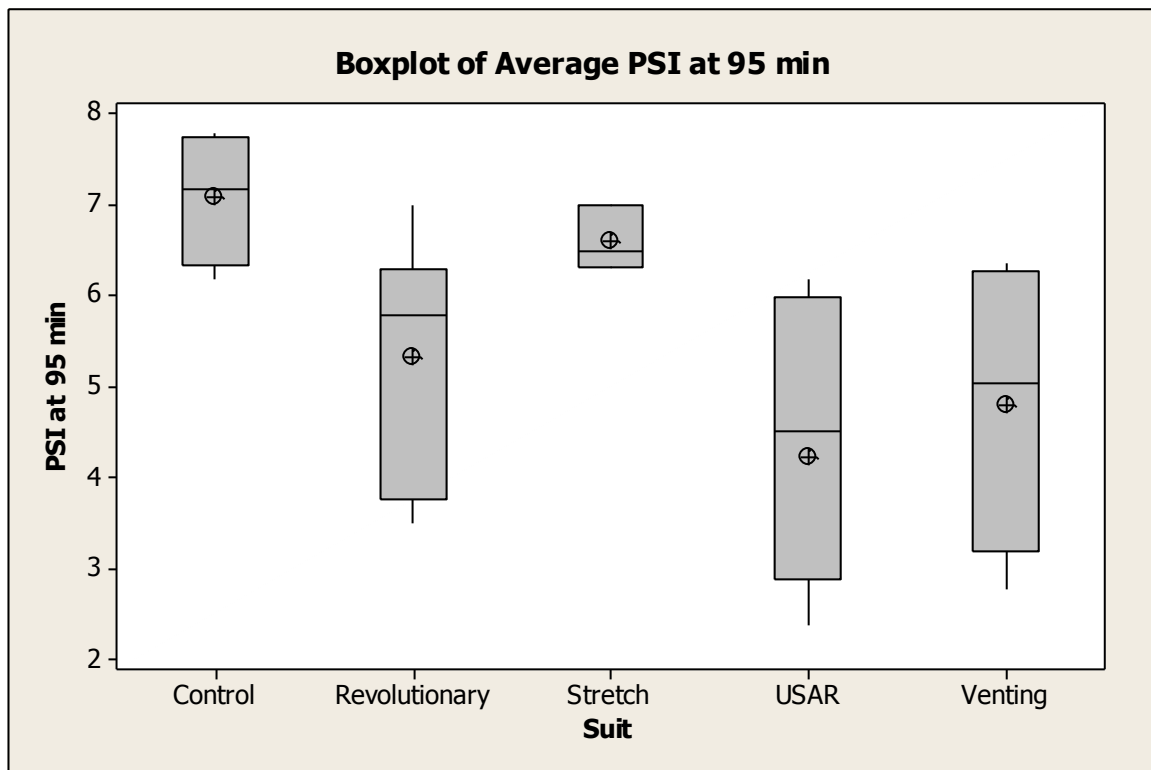


Figure 10-19. Box plot of average PSI at 95 minutes for each suit.

The same trend was realized for the mean skin temperature data but differences were more prominent earlier in the protocol. A neutral thermal environment, when a subject is at rest, would result in a constant skin temperature of 33°C at thermal equilibrium (Cabanac, 1981). At 95 minutes into the protocol, average skin temperatures ranged from 36.3°C for the USAR suit to 37.2°C for the Control. At just 45 minutes into the protocol, the USAR prototype exhibited significantly lower skin temperature than the Control. At the end of the last work cycle (95 minutes), the USAR, Venting, and Revolutionary prototypes all had significantly lower skin temperatures than the Control and Stretch (except Revolutionary). The USAR suit even exhibited significantly lower skin temperature than the Revolutionary turnout, demonstrating the negative impact of the Stretch components in this turnout design. At the end of the protocol, the Control suit was able to effectively cool the wearer during the last five minutes of the rest period and there were no statistically significant differences between the Control and other prototypes. However, the Stretch prototype continued to heat up, illustrated in Figure 10-20 below, which led to a significantly higher skin temperature than the USAR, Venting, and Revolutionary prototypes at 100 minutes.

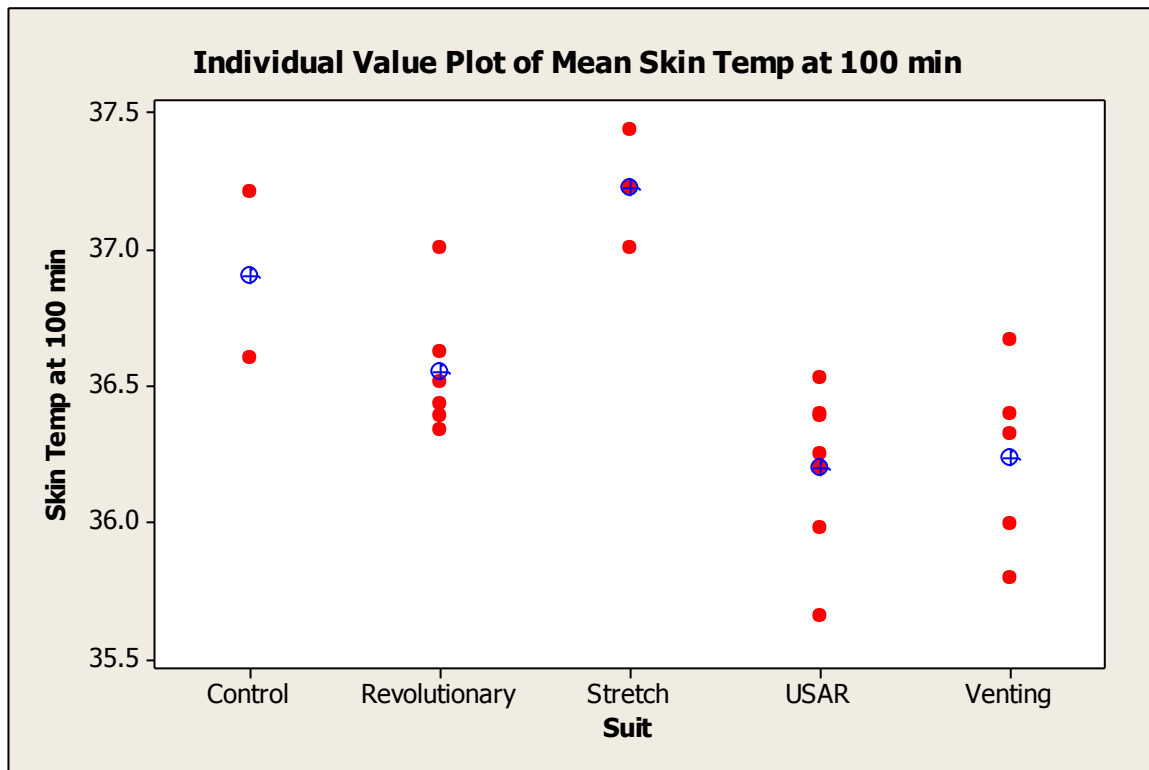


Figure 10-20. Individual value plot of mean skin temperature for each suit at the end of the protocol.

Weight loss between suits was similar, except for subjects wearing the Stretch prototype who lost the least amount of weight, and those wearing the Revolutionary prototype, who lost the greatest amount of sweat. These differences, however, were not significant. The Stretch prototype had the lowest heat loss value, when tested on the manikin on the garment level. This could lead to less weight being lost from the body as effective evaporative cooling of sweat was not able to occur when wearing this prototype and instead, was trapped in the ensemble. This is reflected in the high ensemble weight for the Stretch prototype. For the Revolutionary prototype, which contained the stretch panels combined

with the clothing vents, the higher weight loss could be related to the high evaporative resistance of the stretch component which generated more sweat. The difference in the Revolutionary suit and the Stretch prototype are the addition of vents, which would have allowed for more effective evaporation to occur as they directly exposed the wearer's skin to the environment. This would explain the higher weight loss from subjects when wearing the Revolutionary suit, as more sweat was produced due to the low breathability and increased weight from the Stretch panels, but, in turn, this sweat was able to be effectively evaporated through the vent openings.

Finally, subjective data did not indicate any statistically significant differences in overall average ratings between suits for perceived comfort or perceived exertion.

Temperature sensation results between suits were more pronounced with the USAR having a significantly lower rating than the Control. Overall, the trends in the rating scale results followed those of the physiological responses with the USAR, Venting, and Revolutionary suits being rated as more comfortable, cooler, and requiring less exertion, compared to the Control and Stretch turnouts.

The results from this wear trial study have direct implications for the personal protective clothing industry. Future research should include the continued exploration of a feasible modular approach to be deployed for specific working conditions. Significant reductions in core temperature, physiological strain, and skin temperature when wearing the vented prototype provide justification for incorporation of active ventilation openings. These vents should be activated for heat stress relief only in scenarios where heat and flame exposure are not present, as well as the threat of biological and chemical contaminants. The

hindrance of the stretch material to provide physiological comfort improvements should be further explored to enhance breathability. Specifically, the Stretch prototype should be evaluated in a trial setting where ergonomic improvements are considered as it was not designed to have a direct impact on heat loss. The Revolutionary suit demonstrated significant improvements for comfort, most likely due to the incorporation of clothing ventilation.

11 Establishing a Relationship between Heat Loss and Physiological Strain in Structural Firefighter Protective Clothing Systems

11.1 Introduction

The research discussed previously has included the exploration of garment level design modifications for improved heat loss on the manikin level, predicted physiological responses determined through the use of human thermal modeling software to inform the functional design process, and human wear trial assessments of developed turnout prototypes to evaluate the reduction in heat strain for the wearer. This chapter aims to bring together the systems level methodology approach used in this study by determining the relationship between THL measurements made on a thermal manikin and actualized physiological comfort experienced by the firefighter.

The research objectives of this study were:

1. To investigate optimal clothing modifications, in structural firefighter protective clothing systems, for heat strain reduction.
 - a. To analyze clothing ventilation, layering effects, modularity, and air gap volume for their influence on heat loss in structural firefighter turnouts.
 - b. To determine how additional fabric reinforcements and clothing layers influence heat transfer, on both the fabric and garment levels, in structural firefighter clothing ensembles.

2. To establish a relationship between the heat loss capabilities of structural turnout garments, with various optimal clothing modifications, and changes in physiological heat strain for the wearer.
 - a. To establish a benchmark for the amount of heat loss necessary to achieve a meaningful impact for improved physiological comfort.
 - b. To determine the correlation between predicted physiological responses and measured responses on human subjects as a method for validating the human thermal model.

Objective (1a) was addressed in Chapters 3 through 7 with objective (1b) specifically addressed in Chapters 5 and 6 with the reduced layering and modular approach exploration. The overall question of Objective (1) is answered in Chapter 10 with the wear trial results indicating the physiological comfort improvements of the prototype turnouts which delayed the onset of heat stress. Objective (2), to establish a relationship between heat loss capabilities of turnouts with the respective design modifications and their physiological comfort performance, is initially discussed in Chapter 10 and further analyzed in this chapter. Specifically, objective (2a), is discussed through correlation analyses between garment level THL and measured physiological comfort (heart rate, core temperature, PSI, mean skin temperature, and weight loss). In addition, the modeled predicted physiological responses are correlated with the measured human wear trial responses in order to validate the human thermal model's ability to effectively predict physiological comfort using measurements from the thermal manikin (objective 2b).

11.2 Relationship between Heat Loss and Physiological Strain

The turnout prototypes with design modifications for improved heat loss and physiological comfort were first evaluated on a sweating thermal manikin. Dry and wet heat loss were measured and an overall predicted manikin THL value was calculated for a 35°C/35% relative humidity environment. This methodology assesses the amount of heat flux required to maintain a constant manikin skin temperature of 35°C in all 34 individualized manikin zones. The more heat flux required to maintain the skin temperature, the more heat is being lost to the environment. As discussed in Chapter 2, evaluating clothing ventilation and layering reductions on the manikin level allows for entire clothing ensembles to be assessed and takes into account the amount of surface area covered by various layers, the fit of the garment, and the increased surface area for heat loss (McQuerry et al., 2016). The result is the amount of heat, in W/m^2 , the body is able to lose, in the specified environment, when wearing each of the designed prototype turnouts.

Thermal and evaporative resistance data from thermal manikin tests may then be used to predict the physiological responses of a human body when wearing each respective prototype. But, in order to truly determine the impact of such design modifications on human physiological comfort and heat strain, measurements on the human body when conducting physical exercise are necessary. Therefore, the human physiological wear trial was conducted (Chapters 9 and 10) to determine the differences in heart rate, core temperature, skin temperature, and sweat rate (weight loss) when wearing the standard Control turnout and the prototypes for improved comfort.

To the author's knowledge, previous research has not been completed which connects garment level THL measurements to the physiological performance of structural firefighter turnouts developed with improved comfort designs. Therefore, the relationship between heat loss performance on the thermal manikin should be compared and correlated to the physiological responses measured on the human body, for each suit. This relationship is of most importance as THL values, on the sweating guarded hot plate, are currently used in NFPA standards as a mandate for thermal comfort. As the focus of this research was on novel garment level designs, the base composite materials for each turnout are identical, necessitating heat loss evaluations on the manikin level as the plate is incapable of detecting such changes. This research illustrates the importance of moving towards manikin level THL evaluations as changes in design, fit, and reinforcement layers are not detected by measurements on the plate alone.

11.2.1 Correlation between Garment Total Heat Loss and Human Physiological Response

Correlation analyses were performed using data from the wear trial and the THL results from the sweating thermal manikin testing of the prototype turnouts (Table 11-1). Each of the dependent variables was correlated against each of the independent variables to determine which independent variable predicted the dependent variables best.

Table 11-1. Correlations performed between wear trial responses and manikin THL results.

Dependent Variables	Independent Variables
Average Core Temperature at 95 minutes	Static Manikin THL
Max Rise in Core Temperature	Dynamic Manikin THL
Average Skin Temperature at 95 minutes	
Max Rise in Skin Temperature	
Average Heart Rate at 95 minutes	
Max Rise in Heart Rate	
Average PSI at 95 minutes	
Max Rise in PSI	
Weight Loss	
Ensemble Weight Gain	
Perceived Comfort	
Perceived Exertion	
Temperature Sensation	

Static manikin THL was conducted for each prototype turnout with the manikin standing still and a still air wind speed of 0.4 m/s. Dynamic manikin THL, conducted with the manikin walking at 45 steps/minute in a wind speed of 2 m/s, was more indicative of realistic conditions as firefighters are often moving in environments where air movement is present. Not surprisingly, dynamic manikin THL demonstrated stronger, significant correlations for all dependent variables than did static manikin THL. Table 11-2 gives the correlation coefficient and p-value for dynamic manikin THL and its relationship to each dependent variable. A p-value less than 0.05 indicates significance at the 95% confidence level and is highlighted in red below. Those correlations which are significant at the 90% confidence level are indicated in blue.

Table 11-2. Correlation coefficients for dynamic manikin THL and dependent variables.

Independent Variable	Dependent Variable	Correlation Coefficient <i>r</i>	P-Value
Dynamic Manikin THL	Average Core Temperature at 95 minutes	-0.838	0.077
	Max Rise in Core Temperature	-0.839	0.075
	Average Skin Temperature at 95 minutes	-0.786	0.115
	Max Rise in Skin Temperature	-0.682	0.206
	Average Heart Rate at 95 minutes	-0.832	0.08
	Max Rise in Heart Rate	-0.881	0.049
	Average PSI at 95 minutes	-0.851	0.068
	Max Rise in PSI	-0.846	0.071
	Weight Loss	0.548	0.339
	Ensemble Weight Gain	-0.681	0.205
	Perceived Comfort	-0.888	0.044
	Perceived Exertion	-0.746	0.147
	Temperature Sensation	-0.735	0.157

The only relationship which was significant for the physiological data, at the 95% confidence level, was between dynamic manikin THL and the maximum rise in heart rate. As THL increased, the max rise in heart rate decreased, illustrating the improvement in physiological comfort. Figure 11-1 illustrates this relationship. The prototypes with the high heat loss capabilities (USAR and Venting), led to lower rises in heart rate. The Revolutionary suit, which had the highest THL, did not have the lowest rise in heart rate, most likely due to the burdensome Stretch materials which lessened its ability to release heat to the environment and led to an earlier onset of heat strain.

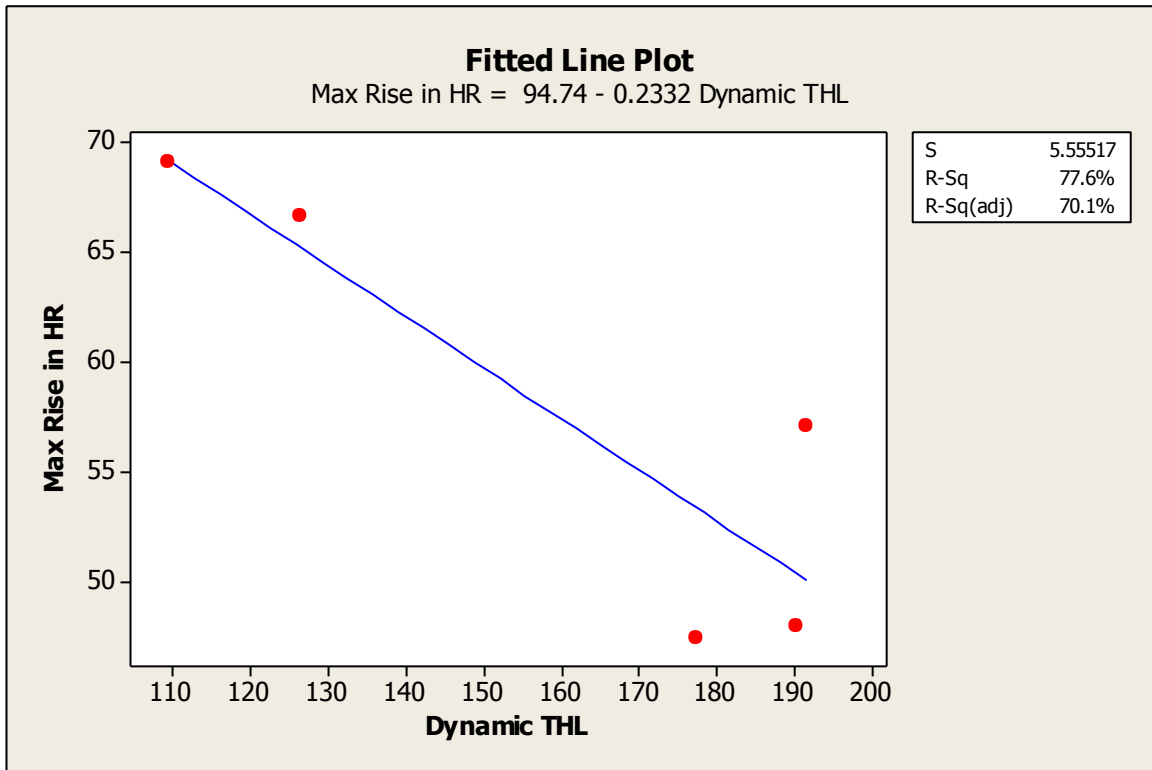


Figure 11-1. Correlation between maximum rise in heart rate and dynamic manikin THL.

The average and maximum rise in core temperature, when correlated with dynamic manikin THL were significant at the 90% confidence level. Figure 11-2 shows the relationship between max rise in core temperature and dynamic manikin THL.

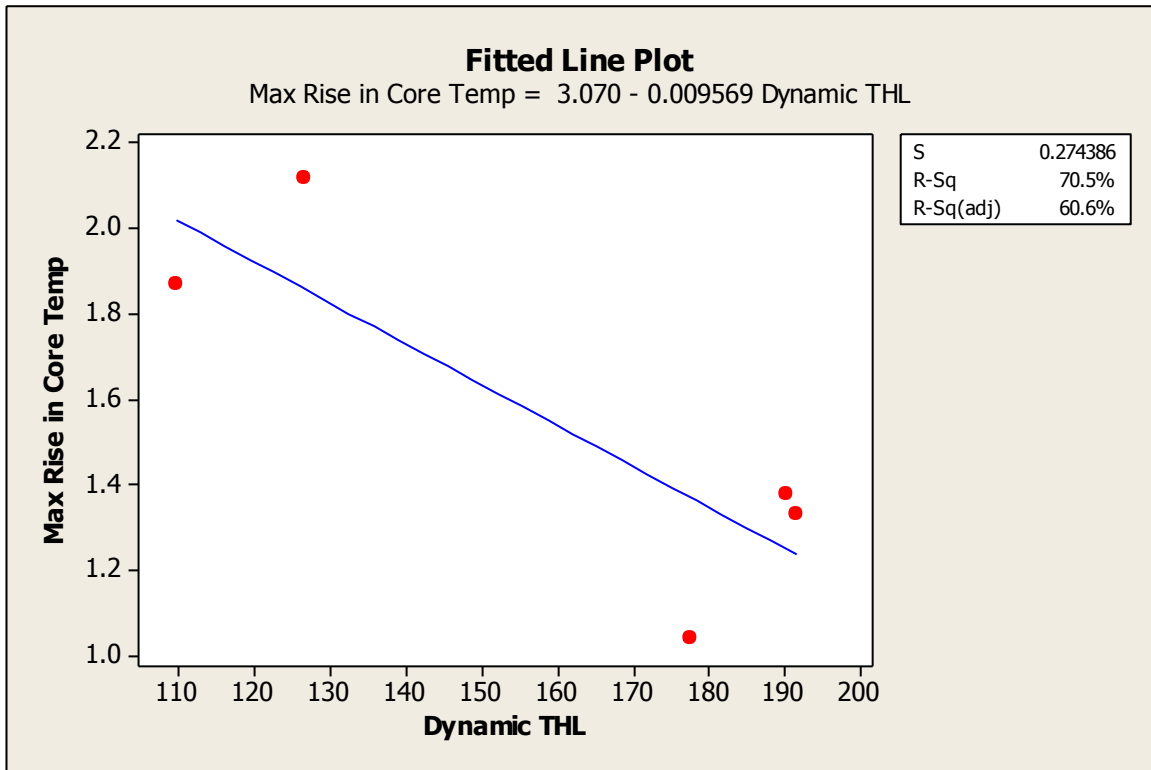


Figure 11-2. Correlation between maximum rise in core temperature and dynamic manikin THL.

The USAR turnout prototype, made of a single outer shell layer, had the lowest rise in core temperature and least amount of clothing insulation. Although it did not have the highest manikin THL value, at some point, an increase in THL will no longer create realized physiological comfort improvements. These results also reflect the optimized performance of ventilation as there is plenty of room between the Control and Ventilated turnout prototypes for balance between comfort and protection. A less exaggerated clothing ventilation design could be implemented into structural turnouts that would require a lesser sacrifice in

protection yet still provide a significant reduction in heat strain by lowering the rise in core temperature.

Similar results were found to be significant at the 90% confidence level for average PSI and max rise in PSI. Those prototypes with higher manikin THL values (USAR, Venting, and Revolutionary) exhibited significantly lower levels of physiological heat strain. Although the sample size (number of suits = 5) is small, this correlation shows a promising relationship between increased heat loss, identified on the sweating thermal manikin, and the corresponding physiological comfort performance.

Linear regression analysis was conducted for the overall average comfort, exertion, and thermal sensation ratings correlated to the static and dynamic manikin THL results, for each suit. A strong, positive ($r = 0.89$) significant ($p = 0.04$) relationship was identified between the perceived subjective comfort rating and the dynamic manikin THL (Figure 11-3). As THL on the manikin increases, the subject's average perceived comfort rating increased with the USAR, Venting, and Revolutionary prototypes being the most comfortable, followed by the Stretch and Control turnouts.

Further analysis was conducted at the end of the third work cycle (70 minutes) to assess subjective ratings. Figure 11-4 illustrates the relationship between temperature sensation subjective ratings at 70 minutes into the wear trial protocol and the predicted dynamic manikin THL of each suit. The correlation between these two factors was not significant ($p = 0.064$), however, 73% of the variation in the subjective thermal sensation rating can be explained by the dynamic manikin THL results. The fitted line plot illustrates an established trend that as garment THL increases, temperature sensation ratings are less

warm, with the exception of the Revolutionary prototype which has the highest THL but is hindered by the burdensome Stretch components which led to a warmer thermal sensation.

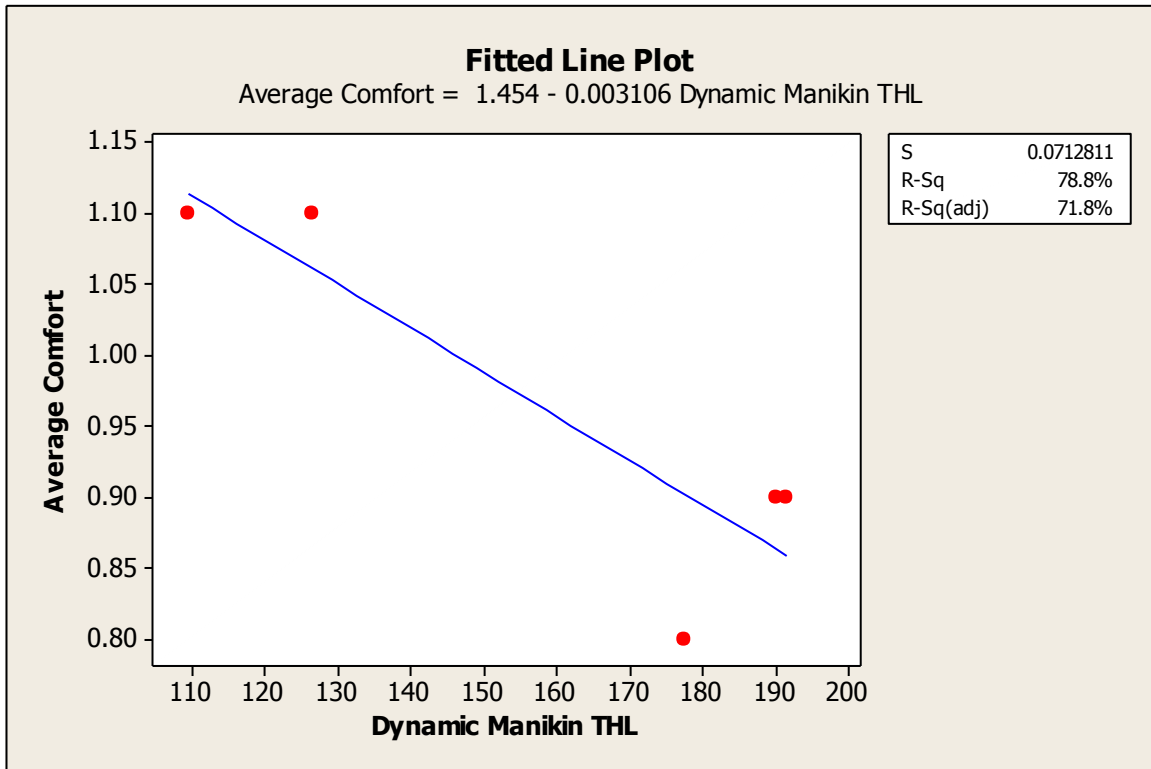


Figure 11-3. Fitted line plot for average perceived comfort and the relationship to dynamic manikin THL for each suit.

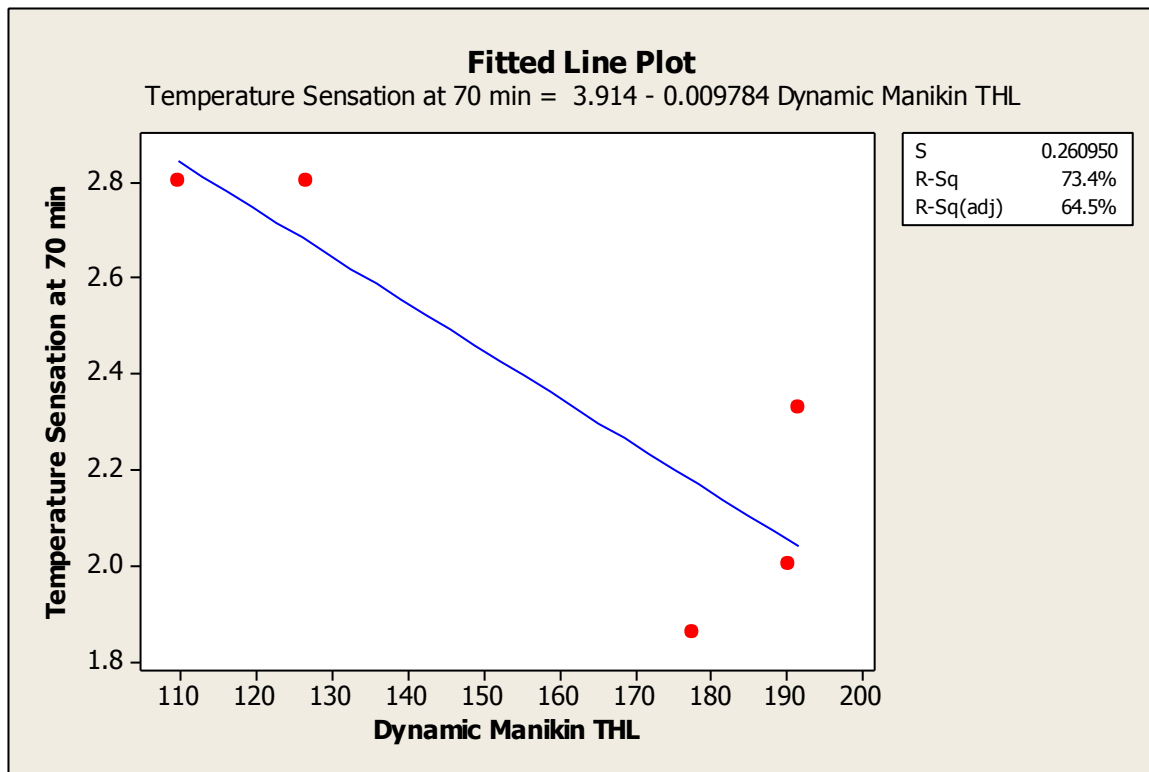


Figure 11-4. Fitted line plot for temperature sensation ratings at 70 minutes and the relationship to dynamic manikin THL for each suit.

Overall, strong correlations between manikin THL and the dependent variables were found for the max rise in core temperature and heart rate. Other research has demonstrated stronger correlation between plate THL and physiological responses (Walker, 2013) even though it does not consider garment level aspects such as design features and fit, which were explored in this study. Limitations to measuring THL on the manikin include the large variability between garments due to layers of air created on the garment level and various accessories placed on different areas of the body (Walker, 2013). However, relying on the plate alone to capture differences on the garment level is insufficient. While the plate detects

differences between fabrics, it cannot decipher designs on the garment level which directly influence heat loss, such as ventilation openings, reinforcements, and variations in air gap volume over the surface of the body. Therefore, further efforts should be made to shift the focus to manikin level THL assessments which consider the entire ensemble, not just the three layer base composite.

11.2.2 Garment THL Benchmark for Firefighter Turnout Comfort

The PSI was calculated and analyzed in order to qualitatively capture the heat strain experienced when wearing each of the suits studied in this research. Comparing the human wear trial measurements to the sweating manikin THL provides insight into how heat loss performance correlates to physiological comfort. Heat exhaustion begins to occur at a core body temperature between 38°C and 40°C (Cabanac, 1981). As shown in Figure 10-4 the average maximum core temperature reached by the suits was highest for the Control at 38.9°C and lowest for the USAR at 38.1°C, a difference of 0.8°C which is not only statistically significant, but meaningful for the wearer's physiological comfort. Table 11-3 gives the dynamic manikin THL, intestinal core body temperature, and PSI of each suit.

Table 11-3. Manikin THL and physiological responses for each suit.

Turnout	Dynamic Manikin THL	Max Core Temperature (°C)	Max PSI
Control	126.4	38.9	7.5
USAR	177.5	38.1	4.7
Venting	190.2	38.2	5.3
Stretch	109.5	38.7	6.9
Revolutionary	191.5	38.3	5.7

The standard Control suit had a manikin THL of 126.4 W/m^2 which was not the lowest of all the suits but corresponded to the highest core temperature and worst PSI rating. The Stretch prototype, which was designed to improve ergonomic performance with increased range of motion, had the lowest manikin THL. This was due to the stretch component materials which had lower plate THL values than the base composite. This suit had the second highest core temperature and second worst PSI rating. The prototype with the lowest core temperature and best PSI rating had a manikin THL value of 177 W/m^2 which was lower than the Venting and Revolutionary suits with the clothing ventilation openings. Although these two prototypes had the highest manikin THL values, and performed very similarly, they did not exhibit the best physiological comfort of all the prototypes developed.

These results illustrate the limits of heat loss. At some point, a THL value lower than 126 W/m^2 no longer negatively effects physiological comfort, in the case of the Stretch prototype at 109 W/m^2 . Similarly, there is an upper limit at which increases in THL do not show improved benefits in reducing core temperature or heat strain. For example, the Venting and Revolutionary prototypes both have dynamic manikin THL values over 10 W/m^2 greater than the USAR prototype, yet subjects wearing the USAR suit exhibited lower levels of strain. Garment designs can be attributed to these differences in results. The reduction in clothing insulation by reducing the system to a single, outer shell layer without reducing the air gap allowed for more evaporative heat loss to occur as the potential for air flow in the microclimate was greater. Clothing ventilation openings showed significant improvements in physiological comfort that were similar to the USAR but not as effective even though the manikin THL values were greater for this design. Particularly, the

Revolutionary prototype performance can be attributed to the clothing ventilation openings and was hindered by the Stretch component panels which were not as breathable and had a much lower THL value. The ventilation openings were able to compensate for this reduction in THL demonstrating improvements in physiological comfort. This is promising when considering adding vent openings into turnouts as material thermal protective performance does not have to be sacrificed and the addition of vents can compensate for the additional stress in environments where thermal exposure is not a threat.

Further research is necessary, with an expanded sample size of suits, to determine a specific benchmark at which manikin THL corresponds to positive physiological comfort improvements. The gap in this study between the Control and Stretch suits at 109-126 W/m² and the USAR, Venting, and Revolutionary suits at 177-191 W/m² is quite large. Figure 11-5 illustrates the relationship between dynamic manikin THL and average core temperature at the end of the fourth work cycle (95 minutes). Subjects in this study were not allowed to continue exercise past 39.2°C and an average core temperature of at least 38°C was reached for all suits in the study. Significant differences in heat loss and physiological comfort improvement, compared to the Control, were found for the USAR, Venting, and Revolutionary prototypes. Of these prototypes, the highest average core temperature reached was 38.3°C.

In order to establish an estimated benchmark for dynamic manikin THL a maximum core temperature value of 38.5°C may be chosen as the point at which physiological comfort improvements begin to be realized when compared to a standard structural firefighter turnout. According to the regression equation in Figure 11-5, a core temperature of 38.5°C is

estimated to correspond to a manikin THL value 147.9 W/m². Therefore, a benchmark of 150 W/m² may be a realistic estimate of the dynamic manikin THL value necessary to achieve a reduction in heat strain. This large gap illustrates the wide opportunity for optimization between commercial suits currently available and the prototypes designed in this study.

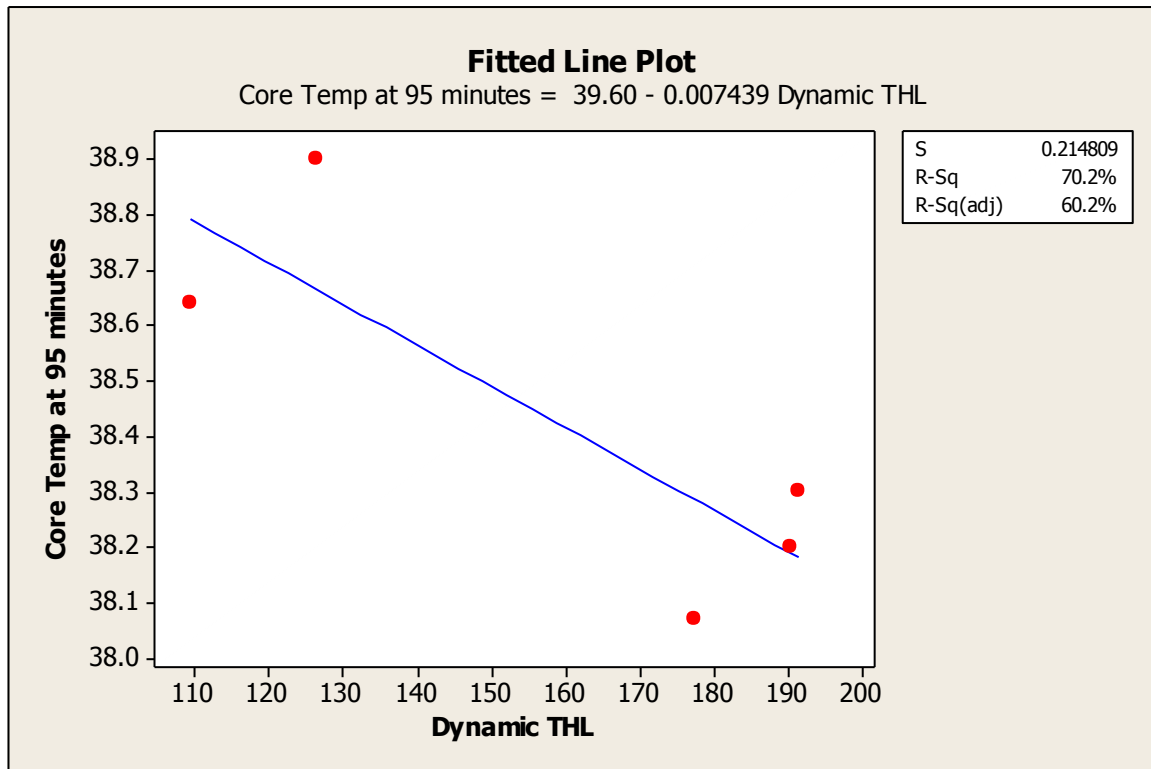


Figure 11-5. Regression analysis of dynamic manikin THL and core temperature at 95 minutes.

A nonparametric distribution analysis was conducted to determine the survivability of the subjects by suit. Nonparametric survival plots display the estimates of the reliability across time, without assuming a distribution. In the survival plot in Figure 11-6, the Y axis

represents the percentage of subjects wearing each suit that are still exercising related to the duration in minutes of exercise on the X axis. Over time, the ability of the subjects to survive decreases for all suits except the USAR, for which all seven subjects completed the full 100 minute protocol.

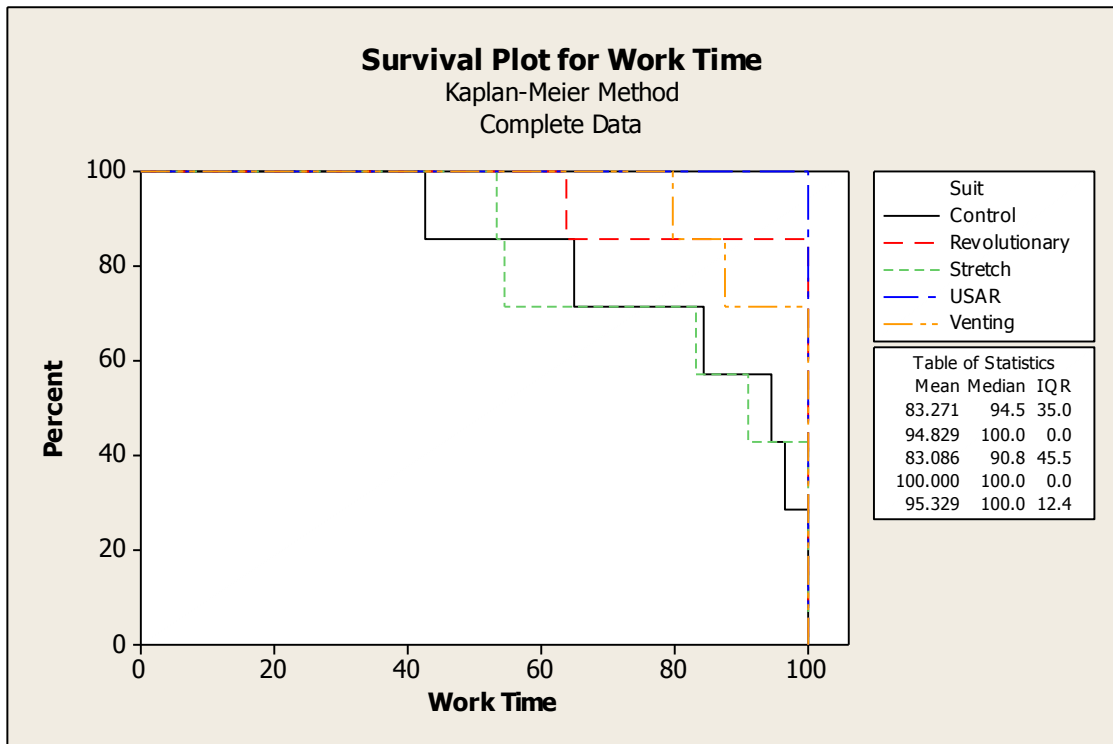


Figure 11-6. Survivability plot for work time for each suit.

The average survival time for the Control and Stretch suits was the same at approximately 83 minutes, followed by the Revolutionary and Venting prototypes at approximately 95 minutes, and the USAR at 100 minutes. The log rank test tests whether

there is a difference in the overall survival between suits by calculating the chi-square and p-values. For this data, the chi-square value was $X^2 = 10.56$ and the p-value was less than 0.05 ($p = 0.032$) indicating statistically significant differences in the survivability distributions between suits.

11.3 Validating the Human Thermal Model

Thermoregulation modeling was used in this study as a down selection tool in the functional design process. The clothing ventilation, bulk variation, layering strategies, and air gap volume experimentation results from the sweating thermal manikin were modeled in the initial specified environment (Table 4-1). Once prototypes were designed, developed, and finalized, they were each evaluated on the sweating thermal manikin and THL was predicted in the same environmental conditions (35°C/35%RH) as the wear trial protocol. Human thermal modeling was conducted to predict the physiological responses in this environment (section 8.4.3).

As discussed in Chapter 2, limited resources such as time and expenses do not allow for human wear testing to be conducted in every possible environment. Thermoregulation modeling may be used as a tool to predict human physiological responses in specified temperature and humidity environments. Thermal insulation and evaporative resistance data for each of the prototypes (Control, USAR, Venting, Stretch, and Revolutionary) was input into RadTherm® software to predict the core body temperature, skin temperature, and sweat rate when wearing each suit.

11.3.1 Correlation between Predicted and Measured Physiological Responses

The measured physiological responses (intestinal core temperature and skin temperature) were correlated with the predicted responses from the human thermal model as a method for validation. Figure 11-3 shows the measured versus predicted core temperature (hypothalamus), for each turnout, over the course of the wear trial protocol.

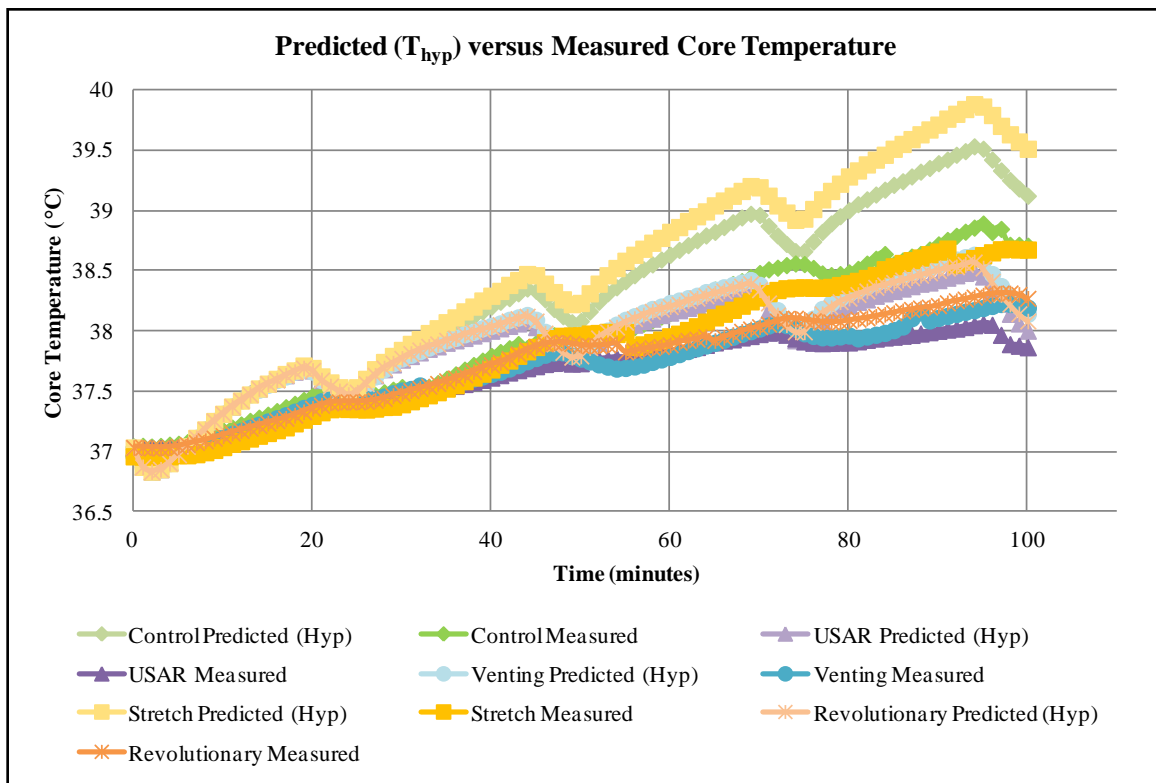


Figure 11-7. Predicted versus measured core temperature results for each turnout.

Figure 11-3 illustrates the similar responses in intestinal core temperature between the human thermal model and measurements taken in the human wear trial, except for the Stretch

and Control suits. In a standard turnout, such as the Control and Stretch prototypes, more ventilation and air flow occurred in practice than was captured by the model and therefore, heat strain was considerably over estimated. Ventilation was a dominant factor for the Vent, USAR, and Revolutionary turnouts and was reflected in the modeled core temperature results. The question of why the model is insufficient in capturing the body's ability to compensate for heat loss in traditional turnouts remains to be answered. Further research is necessary, outside the scope of this work, to determine the intricacies of the model and how it calculates predicted core temperature.

The modeled core temperature results presented in Chapters 4, 5, 6, and 8 are based on predicted hypothalamus core temperature (T_{hyp}) and were used as the main predictor for intestinal core temperature which was measured in the wear trial. The human thermal model also predicts the core rectal temperature. For further analysis in validating the model, both rectal and hypothalamus core temperature were correlated to the measured intestinal core temperature from the wear trial. Figure 11-6 illustrates the predicted hypothalamus, predicted rectal, and measured core temperature for the Control turnout. Table 11-4 gives the end point values and correlation coefficients between the predicted hypothalamus, predicted rectal, and measured core temperature for each suit.

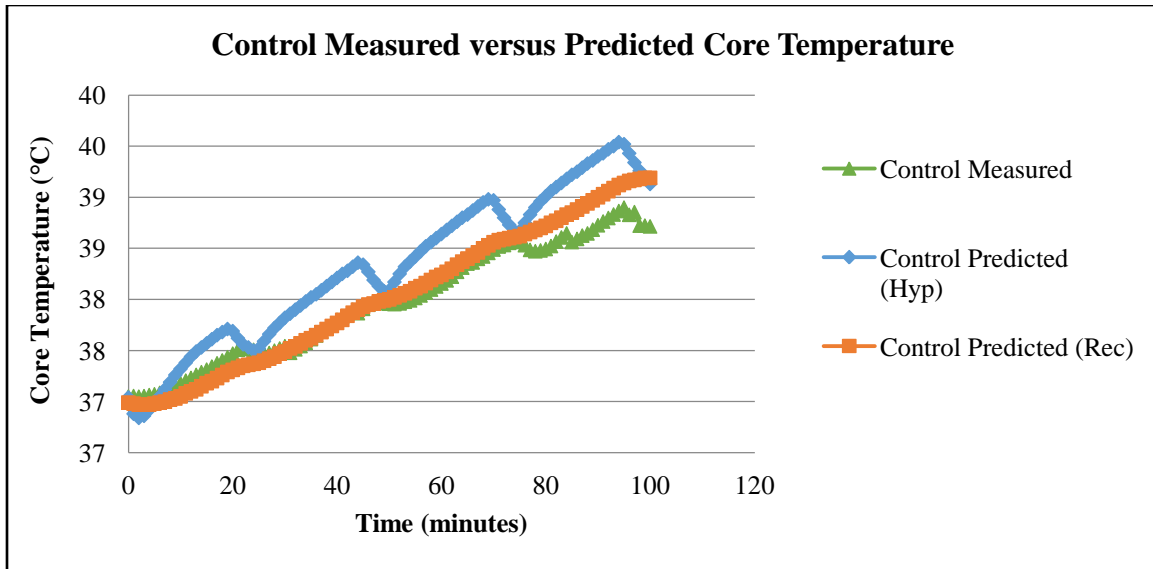


Figure 11-8. Measured versus predicted core temperature for the Control turnout.

The results presented in Figure 11-6 reflect the difference in the modeled core temperature data based upon whether hypothalamus or rectal temperature is used. The predicted rectal temperature more accurately reflect the measured intestinal core temperature as it follows a similar, smoother slope. However, it still over predicts the rise in core temperature after the third work/rest cycle (end of 75 minutes). The rectal core temperature is not as influenced by dips in temperature during the rest cycles as is reflected in the predicted hypothalamus temperature. While some dips were measured in the wear trial, they were not as prominent as what the model predicted.

Table 11-4. Correlations between predicted and measured core temperature.

Turnout	Measured Endpoint Value	Predicted T_{hyp} Endpoint Value	T_{hyp} Correlation Coefficient	Predicted T_{rec} Endpoint Value	T_{rec} Correlation Coefficient
Control	38.72	39.13	0.982	39.19	0.994
USAR	37.87	38.01	0.943	38.36	0.989
Venting	38.20	38.15	0.942	38.47	0.988
Stretch	38.68	39.52	0.982	39.48	0.992
Revolutionary	38.28	38.09	0.928	38.43	0.995

As reflected in Table 11-4 for each suit, a strong, positive correlation was established between the predicted and measured core temperature, regardless of whether the hypothalamus or rectal predicted core temperature was used. Correlation coefficients for the predicted rectal core temperature were stronger for all suits than for the predicted hypothalamus core temperature. The results of the correlations indicate the human thermal model effectively predicts physiological core temperature and is capable of distinguishing between clothing systems. For most suits, the model over predicted the final core temperature of the human subject.

Although gaps in prediction versus measured core temperature were minimal, small variations in core temperature have a meaningful impact on physiological comfort. A difference of just 0.5°C may not be significant, statistically, but from a practical standpoint, a fluctuation of this size in core temperature is significant for the wearer's comfort. While the predicted core temperature correlates strongly with the measured results, room for improvement still remains, especially for the Stretch and Control suits as the model highly

over predicted the core temperature and over exaggerated the drop during rest cycles for the hypothalamus data.

The same correlations were conducted for predicted versus measured skin temperature and are reflected in Figure 11-4 and Table 11-5. Similar results were found for skin temperature but the strength of the correlations was weaker. The same over prediction in temperature was found for the Control and Stretch turnouts. A positive relationship was established between the predicted and measured skin temperature for each suit. Correlation coefficients ranged from 0.73 for the USAR suit to 0.82 for the Revolutionary prototype. For the USAR suit, although end point values are very similar, the start point for the predicted skin temperature was 2°C higher than the average measured skin temperature. This likely led to the overall lower correlation for the skin temperature of the USAR suit. Although the correlations for skin temperature were lower than for core temperature, these results still demonstrate a strong, positive relationship between the predicted and measured results.

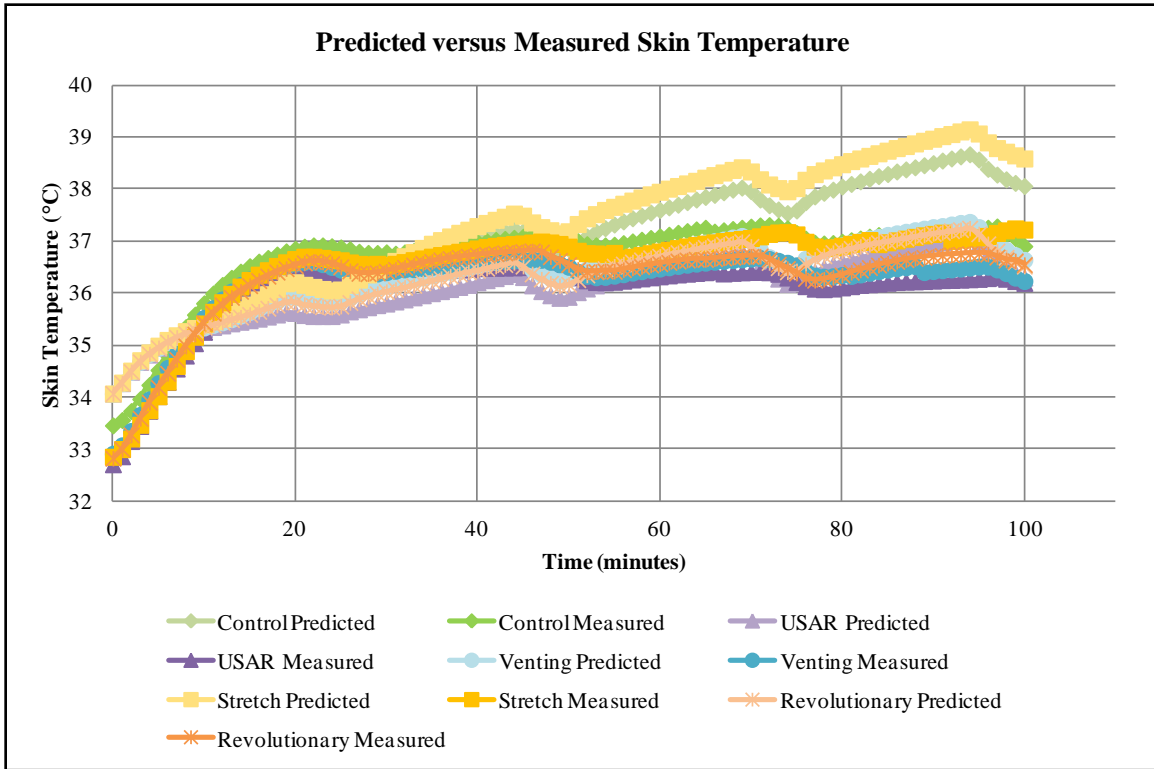


Figure 11-9. Predicted versus measured skin temperature results for each turnout.

Table 11-5. Correlations between predicted and measured skin temperature.

Turnout	Predicted Endpoint Value	Measured Endpoint Value	Correlation Coefficient
Control	38.06	36.90	0.778
USAR	36.30	36.20	0.731
Venting	36.64	36.23	0.783
Stretch	38.59	37.22	0.805
Revolutionary	36.52	36.55	0.819

Overall, these correlations validate the strength of the human thermal model's ability to accurately predict physiological responses in different environmental conditions when

wearing various multi-layer clothing systems. Limitations to the model still exist but it has proven to be a useful research tool, particularly for down selection in the functional design process.

11.4 Conclusion

The correlation between clothing heat loss and physiological strain when wearing structural firefighter turnouts was found to be strongest when compared to the dynamic manikin THL data. This illustrates the importance of conducting sweating thermal manikin evaluations in the most realistic environment possible as the clothing system will be worn. Significant relationships between manikin THL and physiological responses were found for core temperature and PSI at the 90% confidence level and for heart rate at the 95% confidence level. Skin temperature did not exhibit a statistically significant correlation with manikin THL values. These results demonstrate the ability of the manikin level THL test to predict the physiological comfort performance of the ensemble when worn in similar conditions.

As the heat loss of the ensemble increased, for the USAR, Venting, and Revolutionary prototypes, the core temperature, heart rate, and physiological heat strain was reduced. The Control and Stretch turnouts had significantly lower THL values which led to significantly higher core temperature, heart rate, skin temperature, and physiological strain. In an effort to establish a benchmark for manikin THL, at which physiological comfort was significantly improved for the wearer, regression analysis was used. An approximate value of 150 W/m^2 was determined to correspond to a core temperature of 38.5°C . Heat exhaustion begins to occur between 38°C and 40°C making 38.5°C a realistic cut off point for comfort

when wearing such multi-layer protective clothing ensembles. The distance between the Control and Stretch turnouts and the significantly improved USAR, Venting, and Revolutionary prototypes leaves sufficient room for optimization. A combination of reduced layering, ventilation designs, and modularity could be designed to provide a significant improvement in heat loss while lessening the sacrifice of protection currently incorporated in the prototypes for this study.

The survivability plot shows the work times for each suit and when each subject dropped out of the protocol due to one of the aforementioned cut off criteria. Subjects wearing the Control suit dropped out of the protocol first, followed closely by the Stretch prototype, then the Revolutionary and Venting prototypes. All seven subjects included in the statistical analysis were able to continue work until the maximum cut off time of 100 minutes without reaching 90% of their maximum heart rate or a core temperature greater than 39.2°C. A p-value of 0.032 in the log rank test indicated a statistically significant difference in the survivability between suits. This analysis is an additional research tool that can be used to predict work times when related back to the manikin THL values of each suit. Those prototypes with higher levels of THL allowed subjects to "survive" or work for longer periods of time. This illustrates the effectiveness of the modular and venting design modifications to increase working time.

Finally, the measured physiological responses (core and skin temperature) were correlated to the predicted responses gathered from the human thermal model to validate its ability to accurately estimate the wearer's comfort. Strong correlations were found between predicted and measured responses, especially when comparing the predicted rectal body

temperature to the measured intestinal core body temperature. Results from this study suggest the modeled rectal body temperature more closely predicts the measured intestinal core body temperature than the predicted hypothalamus core temperature.

In conclusion, the physiological wear trial demonstrated significant improvements in comfort for the prototypes with design modifications for increased heat loss. These differences were strongly correlated with dynamic manikin THL demonstrating a negative relationship meaning that as manikin THL increases, heat strain decreases.

12 Conclusions

Structural firefighter turnouts are multi-layer clothing systems that provide thermal, liquid, and chemical protection for the wearer. The majority of illnesses and injuries sustained by firefighters today are due to heat strain when wearing such ensembles (Rossi, 2001). Therefore, this research study investigated clothing design modifications for heat loss improvement for the purpose of reducing the risk of physiological heat strain for firefighters when wearing structural turnout clothing ensembles.

As outlined in the Chapter 2 review of literature, heat strain poses problems in multiple types of protective and industrial clothing. Previous examples of clothing ventilation in other areas of functional apparel were reviewed and gathered as inspiration for the ventilation designs evaluated in Chapters 3 and 4. The sweating thermal manikin measurement method was used to determine manikin level THL of different clothing ventilation designs. Results from this experiment determined that passive open vents led to the largest improvement in THL but required the greatest sacrifice in protection. Active ventilation designs were found to have statistically significant benefits for increased THL, compared to the standard Control turnout, but required less sacrifice in protection.

Further alternative methods for analyzing clothing ventilation were explored in Chapter 4 through the use of isolated manikin zone THL ratios, human thermal modeling, and estimated direct ventilation values. These results led to the same conclusion that the active zipper and active vertical ventilation designs made a significant improvement in heat

loss and were predicted to lead to a reduction in the heat strain experienced by the firefighter when wearing such an ensemble.

The second design modification for potential heat loss improvement was the strategic analysis of the reduction of layers, specifically of additional reinforcements. Fabric level THL and TPP testing demonstrated the detrimental effects of additional padding, trim, labels, and layers which lead to unnecessarily high levels of TPP and drastically reduce the breathability of the system. These conclusions were confirmed on the garment level through manikin THL assessments which found turnouts with additional layers and thickness, or "bulk", had significantly lower levels of heat loss. The reduction of additional layers, including internal reinforcements and pockets, however, did not lead to a significant improvement in heat loss performance, directing the researcher to conduct the analysis in Chapter 6 of whole garment layer reductions.

A modular systems approach was adopted for assessment in which the reduction of each whole garment base composite layer was analyzed. The investigation of single, double, and a re-arranged three-layer systems was performed on the sweating thermal manikin and modeled to predict the physiological responses. With each reduced clothing layer, regardless of material content, significant improvements in THL were detected, as to be expected based upon the fundamental properties of clothing insulation. It was surprising to conclude that the removal of the moisture barrier did not result in any greater benefit than the removal of the thermal liner. Meaning, regardless of permeability, a reduction by a single layer led to the same performance in manikin THL. It was concluded that the single layer outer shell garment

was the most realistic to be implemented into the fire service as it represents current USAR systems on the market today.

With the reduction in clothing layers, the question of air layers arose and how they affect heat loss, as well. In order to quantify the impact of reduced air gap volume, a proprietary tight fit moisture barrier was assessed, along with a tighter fitting knit thermal liner substitute. The traditional three layer arrangement was not able to be tested as the moisture barrier was so tight fitting it could only be implemented as a next-to-skin concept, with the knit thermal liner worn on top, followed by the outer shell. Results of the investigation of this particular design modification did not show any significant benefits when wearing the tight fit moisture barrier in conjunction with the three layer clothing system. When compared solely to a traditional, single layer moisture barrier, significant increases in THL were measured.

The completion of Chapter 7 concludes the investigation of the four clothing design modifications: ventilation openings, strategic layering reductions, modularity, and reduced air gap volume. The functional design process was then implemented as a tool for developing prototypes with improved heat loss and physiological comfort. An interaction matrix was used to directly identify contradictory modifications. From there, a digital logic decision making tool assigned quantitative ratings to various design concepts, allowing the researcher to rank the proposed prototype designs. Through the use of the functional design process, four finalized prototype designs were established. The USAR prototype was a single, outer shell layer used to evaluate the modular systems approach. The Venting design was a combination of the active zipper and active vertical ventilation designs originally tested in

Chapter 3. The Stretch design was a combination of air gap volume reduction and improved ergonomic concepts. A tapered fit was implemented with stretch fabric panels in designated areas. Finally, a Revolutionary modern turnout prototype was designed which combined the Venting design, Stretch design, and also incorporated the removal of the thermal liner in the coat torso region. Prototypes were each tested for manikin THL and modeled to predict their physiological comfort performance in the same environmental conditions as the physiological wear trial which were specified in Chapter 9.

The results of the physiological wear trial demonstrated statistically significant reductions in heat strain for the USAR, Venting, and Revolutionary prototypes throughout the 100 minute protocol. Compared to the Control, all prototypes except for the Stretch suit had significantly lower core temperature, skin temperature, and PSI. Work time is a response in and of itself as it demonstrates how long subjects can survive when wearing each suit. All subjects survived the full protocol when wearing the USAR prototype, followed by the Venting and Revolutionary turnouts.

A strong, inverse relationship between dynamic manikin THL and physiological responses was established for the core temperature, heart rate, and PSI data. The gap in THL and physiological responses between the Control suit and the USAR, Venting, and Revolutionary prototypes illustrates the opportunity for optimization that exists. There is a 50-70 W/m² gap between the dynamic manikin THL of the Control turnout and the prototypes which showed beneficial improvements. Therefore, design modifications that may be more likely to be initially adopted by the fire service should be implemented and significant benefits in physiological comfort still realized.

Regression analysis established an estimated benchmark for improved comfort performance of approximately 150 W/m^2 on the manikin level, in dynamic conditions. This value should be of interest to those designers, product developers, and manufacturers conducting research and development for continuous improvement. This value also informs the standards community of an ideal value to aim for when testing structural firefighter turnouts on the manikin level, assuming similar environmental conditions. Finally, the correlation between predicted and measured responses from the human thermal model and the human wear trial provide validation for the model's accuracy in effectively estimating the comfort performance of multi-layer clothing ensembles.

This research is relevant for firefighters, departmental PPE managers, designers and manufacturers of multiple types of functional clothing, and researchers conducting studies around clothing insulation and heat loss. Conclusions from this study not only demonstrate the benefits of the clothing design modifications when applied to structural firefighter turnouts but it validates methodologies, establishes new and alternative methods, and provides original and useful knowledge to the textile and apparel industry for multiple applications.

12.1 Limitations

A limitation of this study is the small sample size and the exploration of only one environmental condition. Time and expenses do not allow for testing in multiple scenarios and conditions with large sample sizes of subjects. Repeats of this study should be conducted on more subjects and in additional environments to determine if the significant improvements in performance exist beyond a replicated vehicle extrication scenario. Related to this

limitation is the response of participant elimination as test termination criteria are reached during the protocol. This reduces the sample size over time which weakens the power of statistical analysis as the number of subjects wearing each suit varies throughout the protocol.

A major limitation to the air gap volume reduction research was the lack of substitute for the outer shell as it was a traditional fitting garment, with no design modifications for slimmer fit. Additional research should be conducted with a slimmer fitting outer shell in order to determine if more benefits are realized with such a design.

Regarding the implementation of design modifications, those included in this study are limited to non-structural firefighting situations only. Ventilation openings should not be actively opened during a structural fire, nor should a single layer USAR design be worn when the threat of thermal exposure exists. Additional modifications for direct application in a structural fire scenario should be explored. Finally, the material selection for the stretch component panels was limited by the availability from the manufacturer and the prototype manufacturing timeline.

12.2 Future Research

Each individual experiment in this study may lead to additional future research opportunities. For clothing ventilation, the exploration of spacer fabrics within the clothing microclimate should be investigated. Such a concept should be explored as a potential way for increasing convective air flow in areas under compression, such as underneath the SCBA and its straps. The modular systems approach proved to be beneficial for significantly improving wearer physiological comfort. However, much research remains to design and implement a full three layer modular turnout that can be easily transformed in the field

between service calls. In conjunction with this concept, the effect of base layers, worn underneath the turnout, should be considered for their contribution to thermal protection and heat loss performance. Considering these clothing layers as part of the turnout ensemble provides multiple opportunities for additional reduction of materials and layers without sacrificing protection. Similarly, additional investigation of air gap volume should be conducted with a comprehensive tighter fitting system including the outer shell.

While correlations between the predicted and measured physiological responses were strong, additional questions remain regarding the fundamental calculations used by the human thermal model. Room for improvement still exists in closing the gap, especially for skin temperature predictions.

Finally, the consideration of female firefighters and their user needs should be addressed. This study focused only on the design needs of structural firefighter turnouts for male firefighters. Literature exists demonstrating the difficulties experienced by female firefighters due to the poor fit of their gear which leads to reduced range of motion and may in fact, quicken the onset of heat strain. A similar research study should be conducted to determine how female firefighters are effected physiologically by their PPE.

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APPENDICES

Appendix A: Manikin THL Ratios for Vented Suits by Test Condition

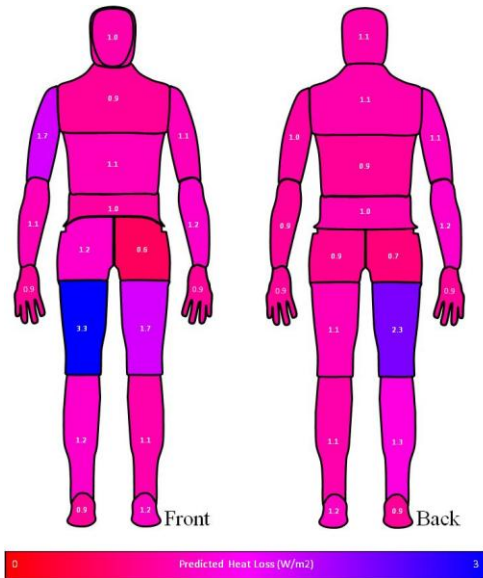


Figure A-1. Passive open vent THL ratio in static test condition.

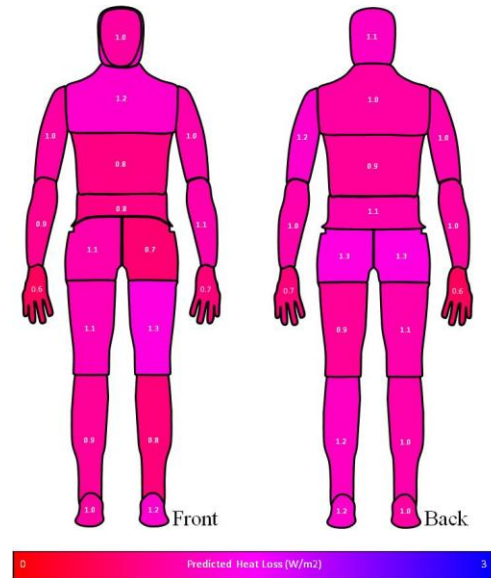


Figure A-3. Active zipper vent THL ratio in static test condition.

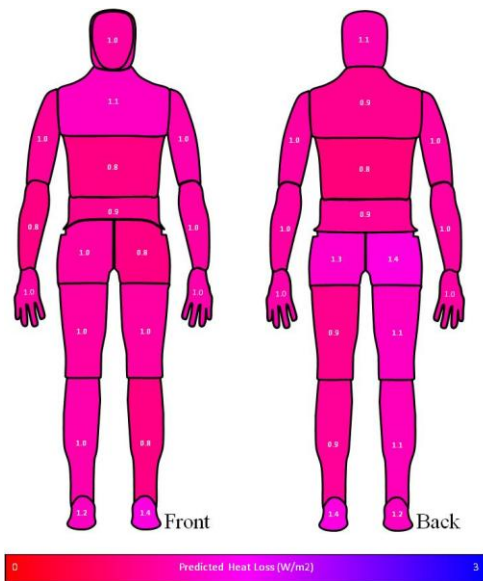


Figure A-2. Passive moisture barrier vent THL ratio in static test condition.

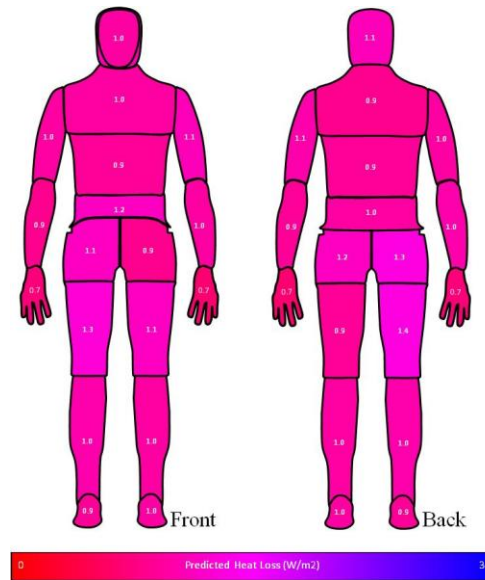


Figure A-4. Active vertical vent THL ratio in static test condition.

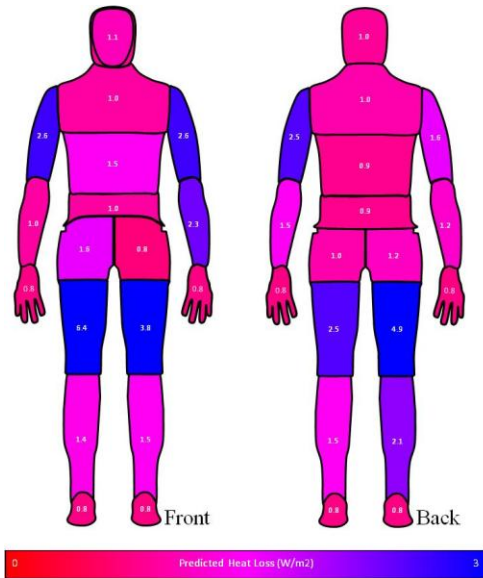


Figure A-5. Passive open vent THL ratio in standing with wind test condition.

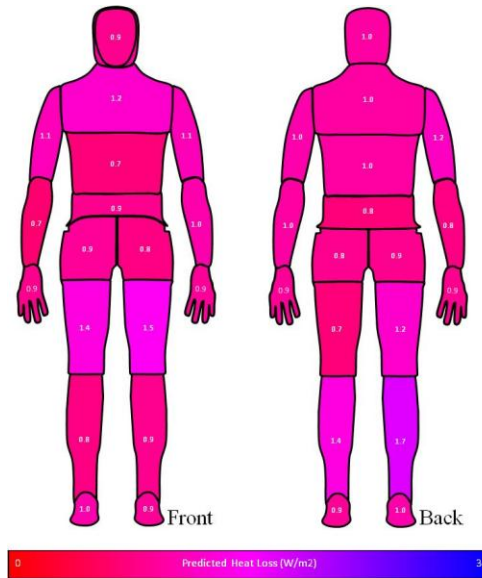


Figure A-7. Active zipper vent THL ratio in standing with wind test condition.

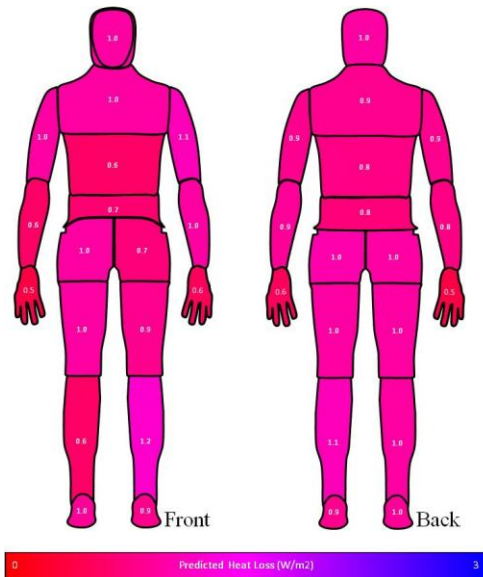


Figure A-6. Passive moisture barrier vent THL ratio in standing with wind test condition.

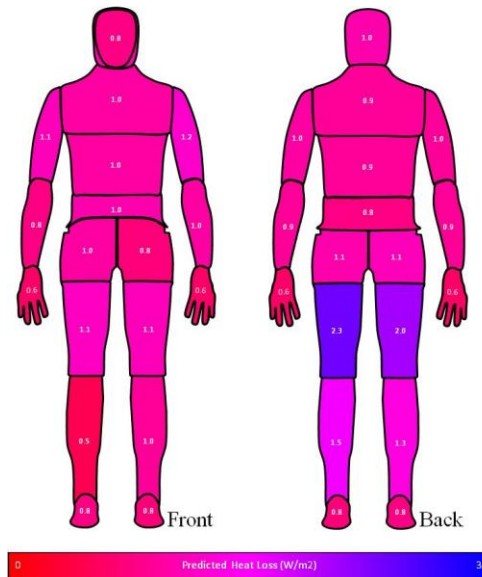


Figure A-8. Active vertical vent THL ratio in standing with wind test condition.

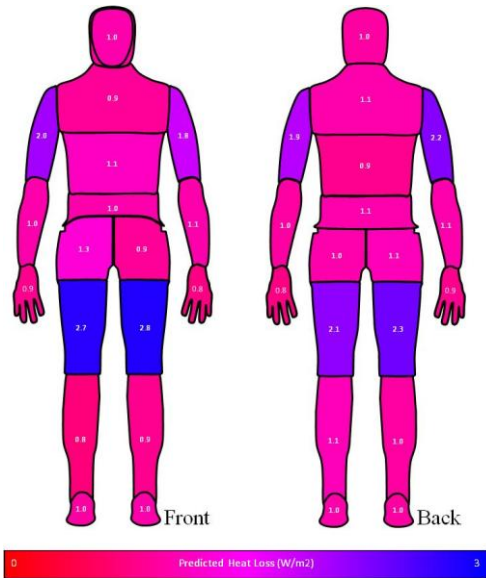


Figure A-9. Passive open vent THL ratio in walking no wind test condition.

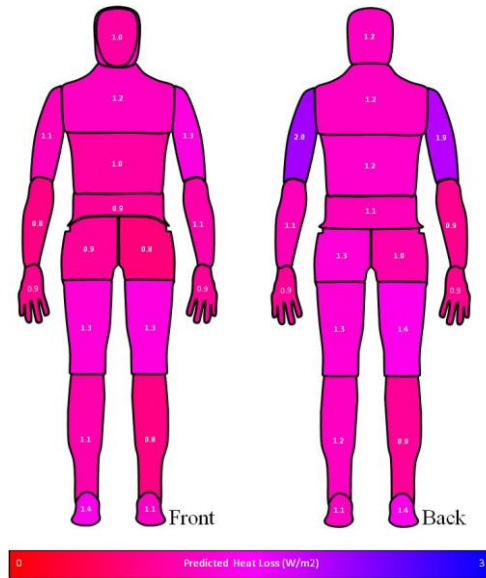


Figure A-11. Passive rivet vent THL ratio in walking no wind test condition.

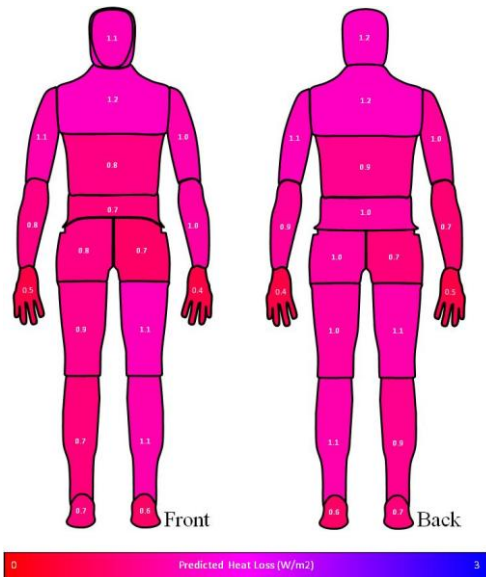


Figure A-10. Passive moisture barrier vent THL ratio in walking no wind test condition.

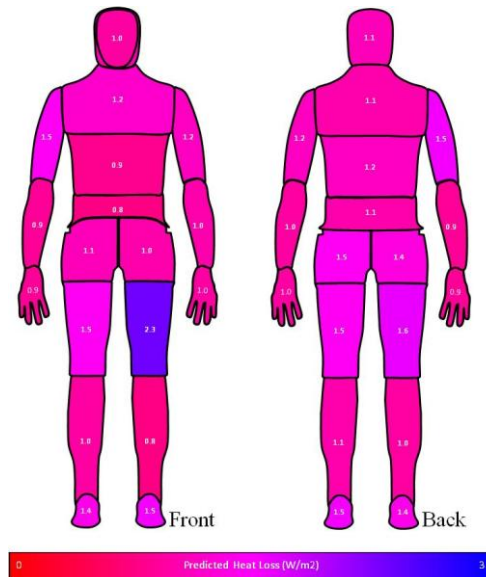


Figure A-12. Active zipper vent THL ratio in walking no wind test condition.

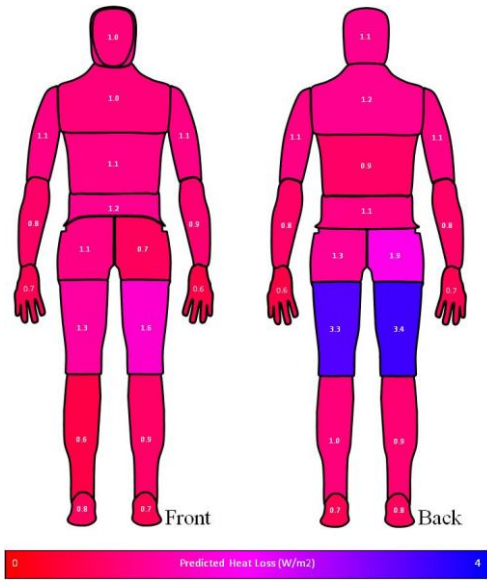


Figure A-13. Active vertical vent THL ratio in walking no wind test condition.

Appendix B: Predicted Physiological Responses of Vented Turnouts

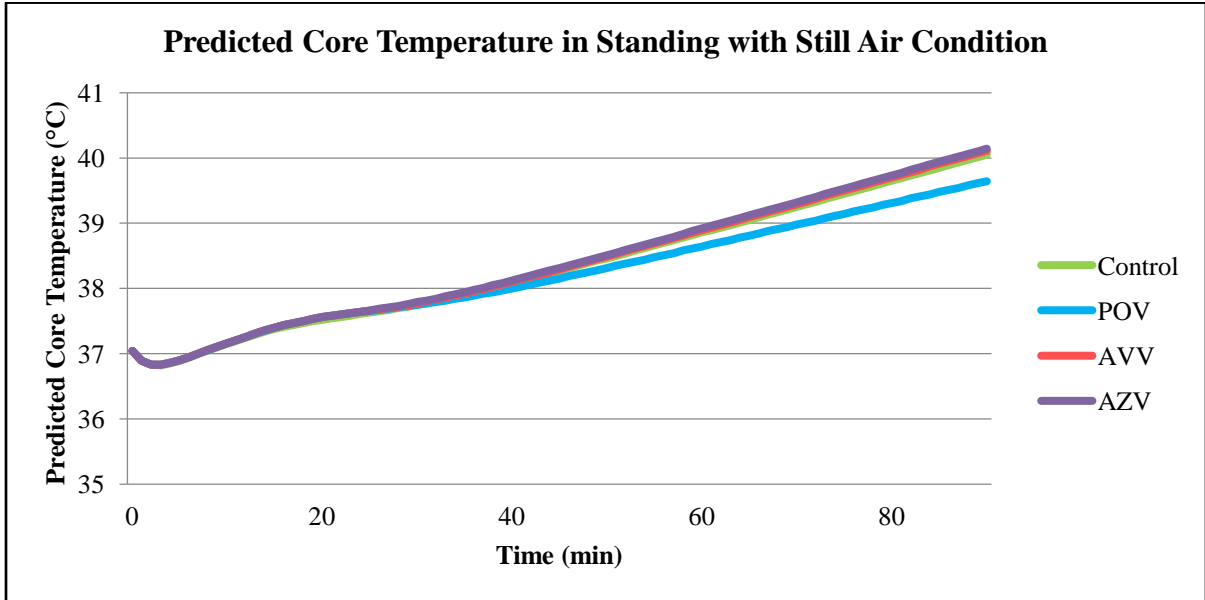


Figure B-1. Predicted core temperature of each vented suit in standing with still air test condition.

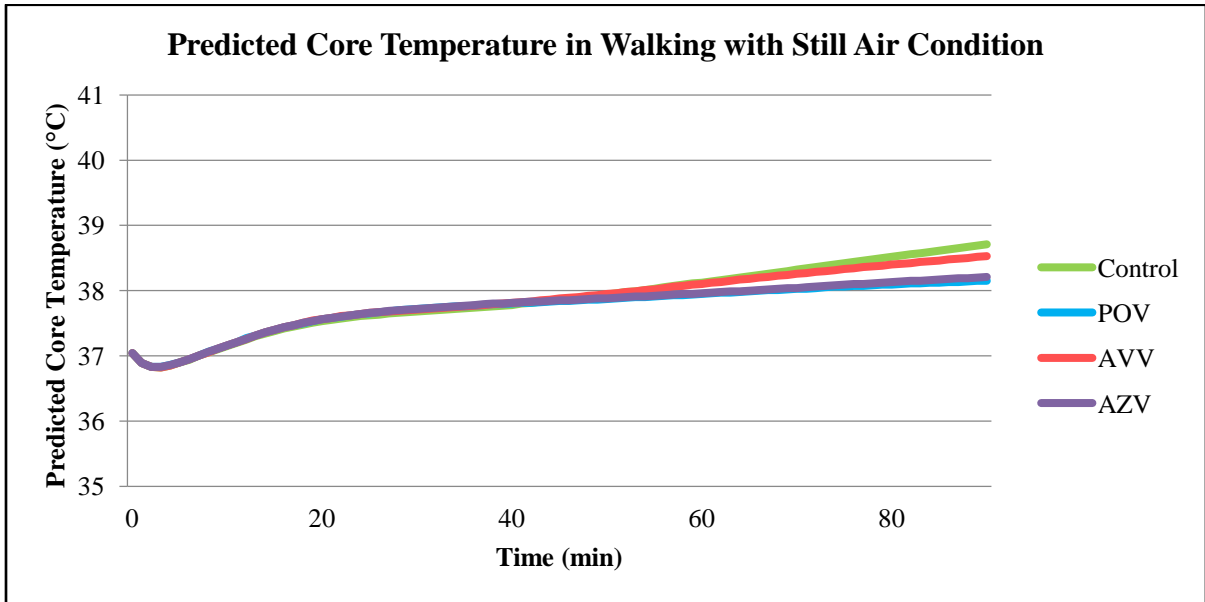


Figure B-2. Predicted core temperature of each vented suit in walking with still air test condition.

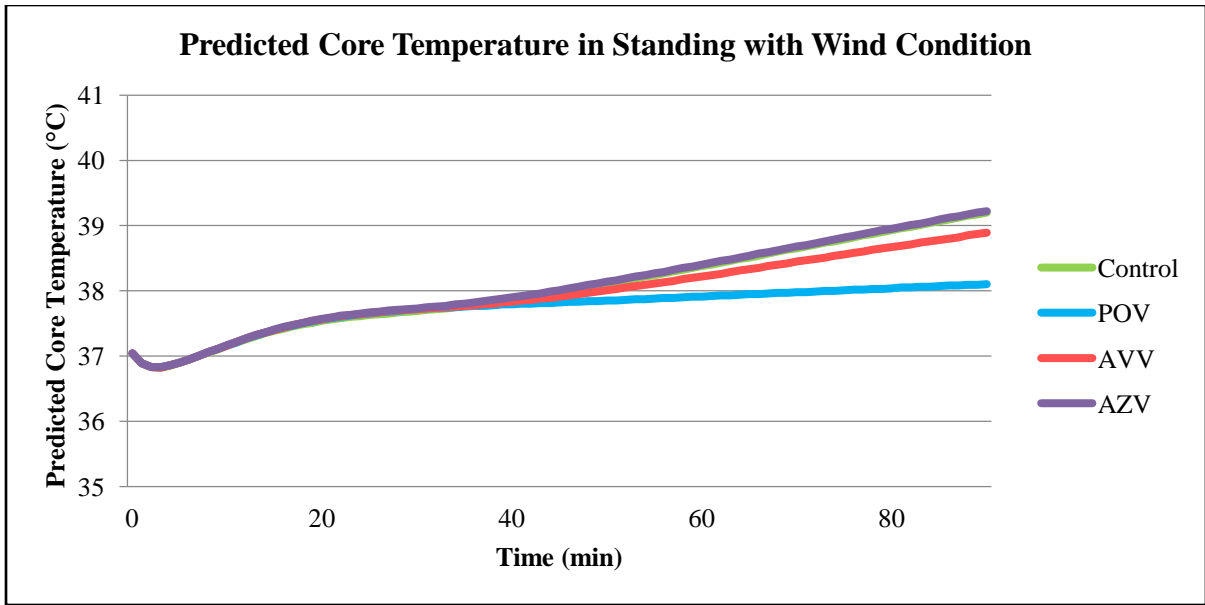


Figure B-3. Predicted core temperature of each vented suit in standing with wind test condition.

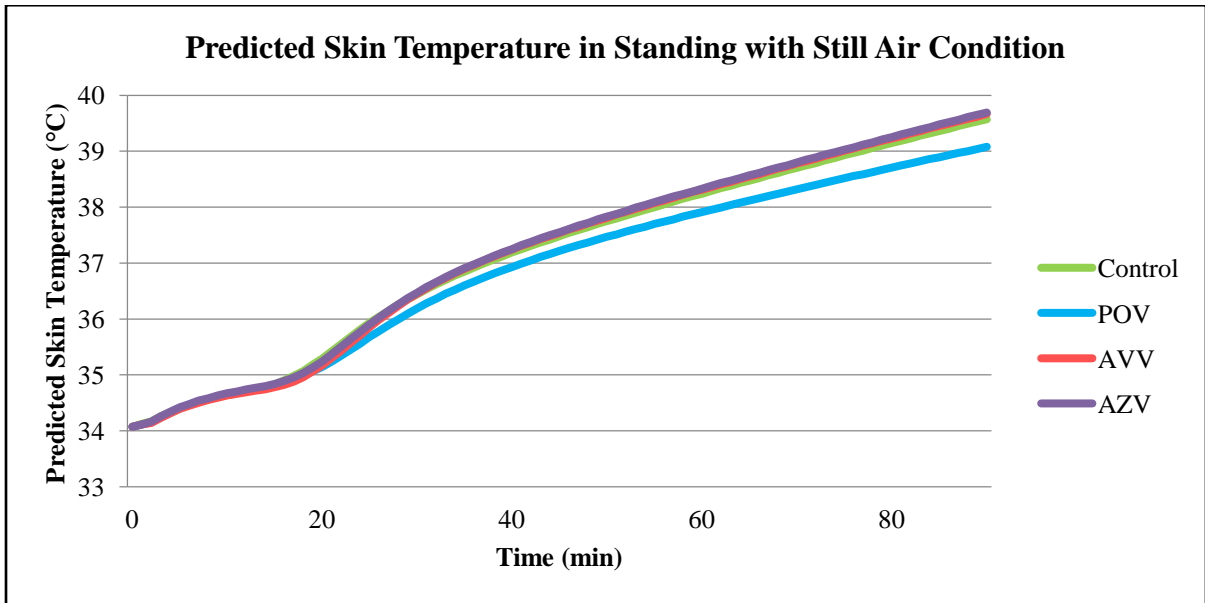


Figure B-4. Predicted skin temperature of each vented suit in standing with still air test condition.

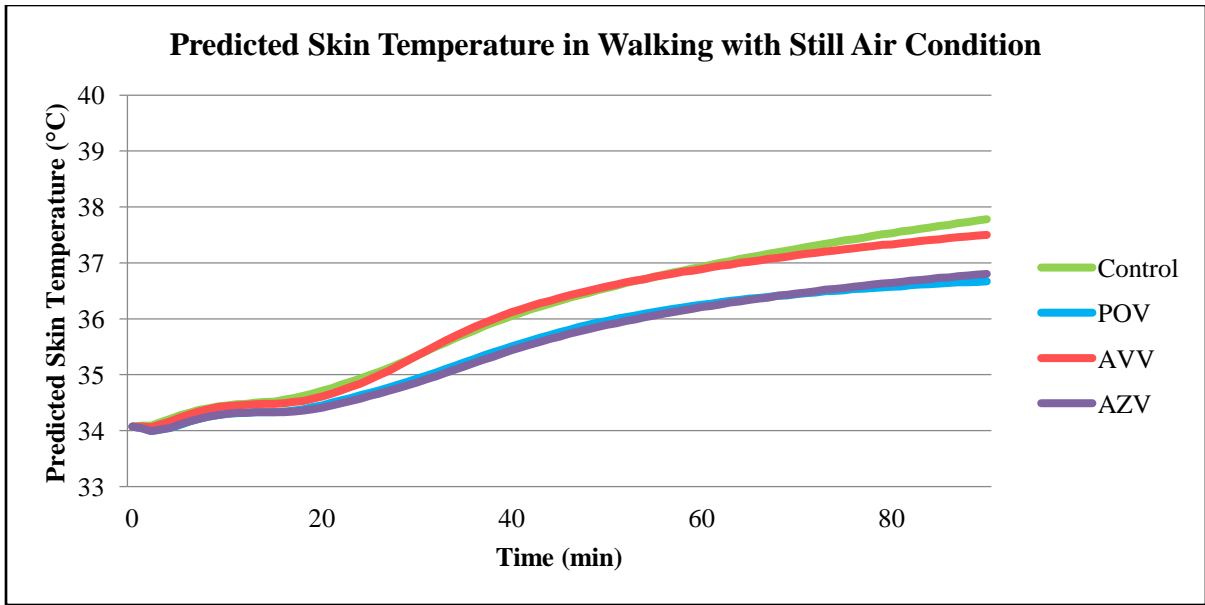


Figure B-5. Predicted skin temperature of each vented suit in walking with still air test condition.

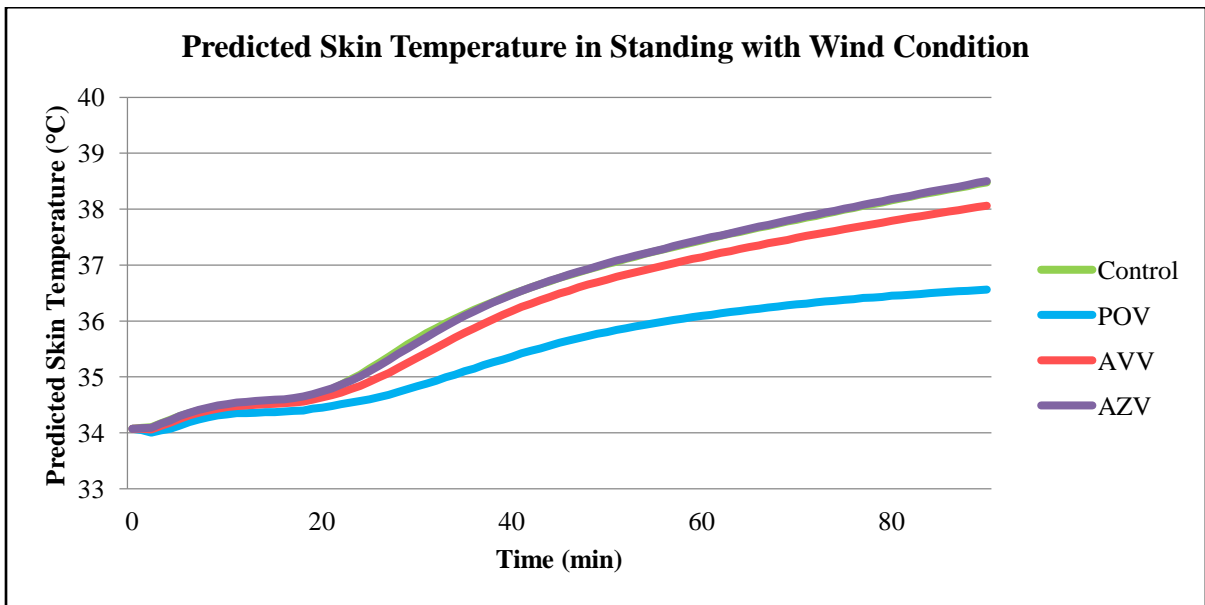


Figure B-6. Predicted skin temperature of each vented suit in standing with wind test condition.

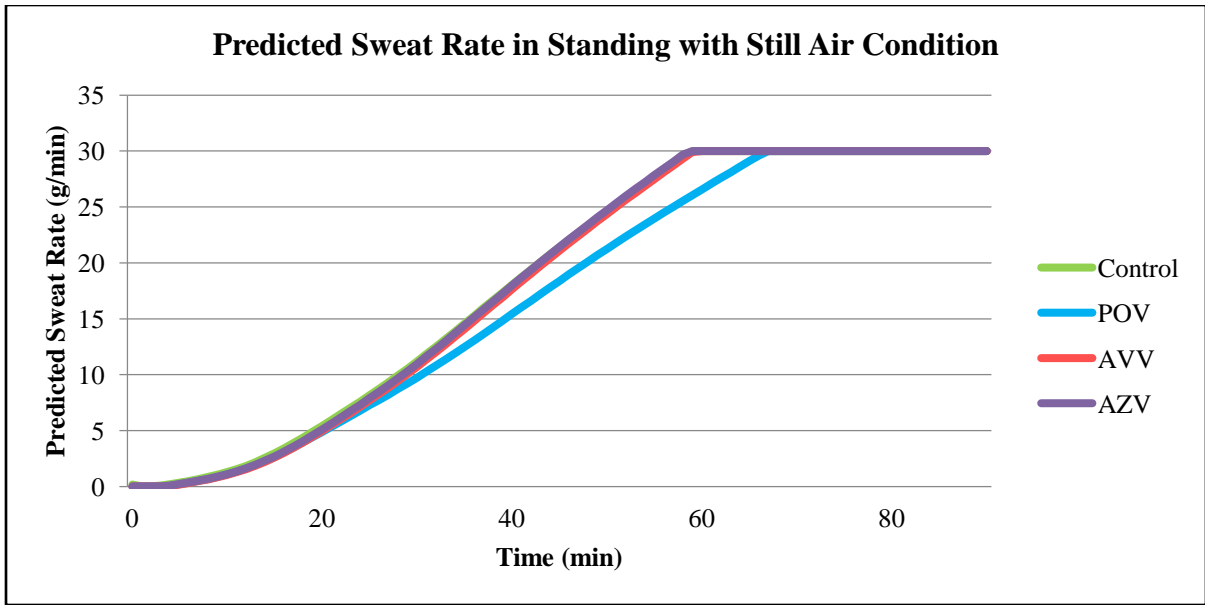


Figure B-7. Predicted sweat rate of each vented suit in standing with still air test condition.

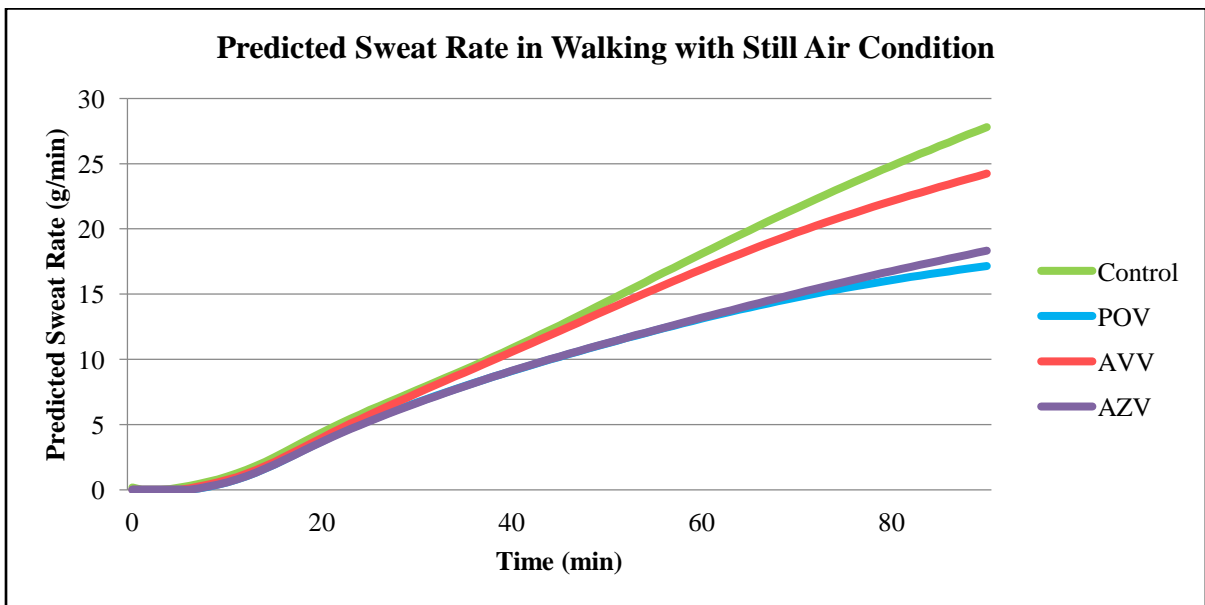


Figure B-8. Predicted sweat rate of each vented suit in walking with still air test condition.

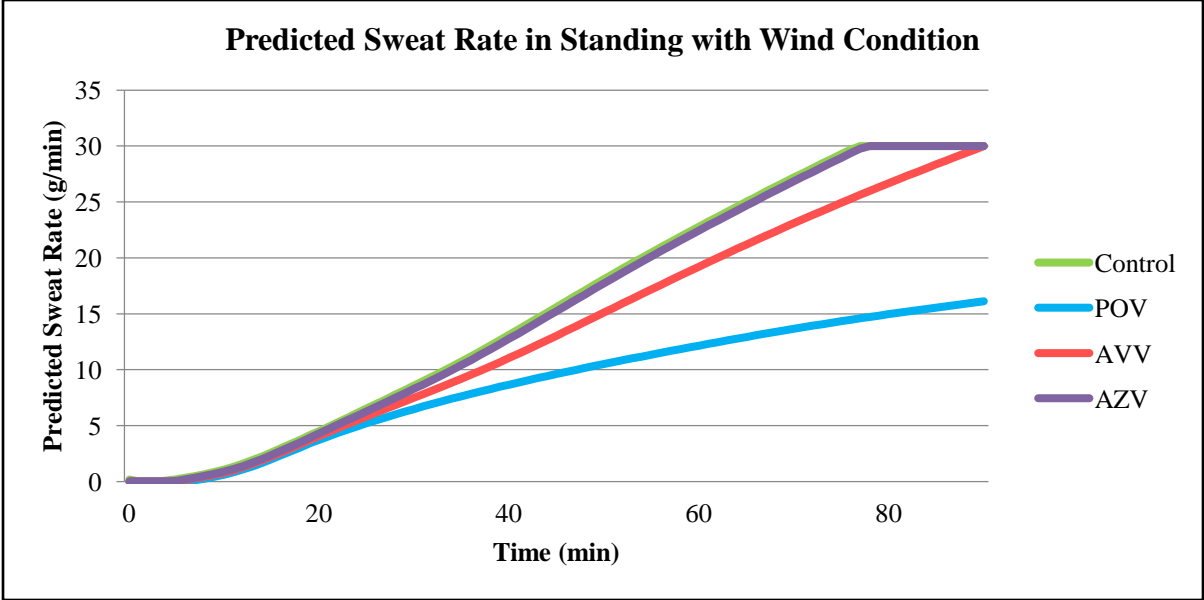


Figure B-9. Predicted sweat rate of each vented suit in standing with wind test condition.

Appendix C: Predicted Physiological Responses of Varied Bulk Turnouts

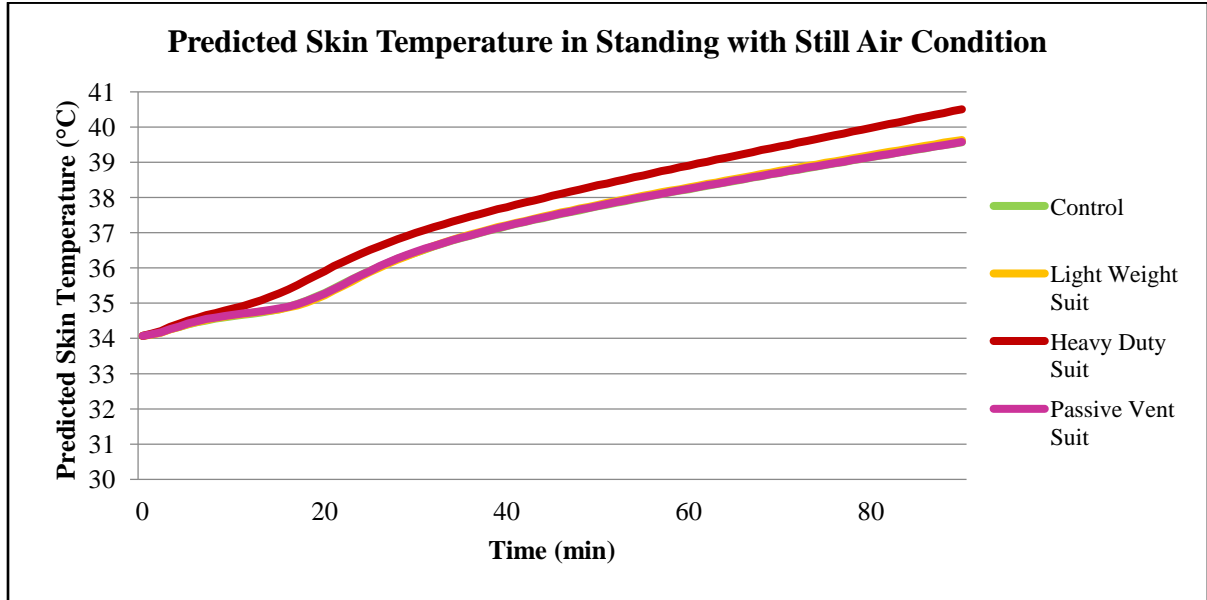


Figure C-1. Predicted skin temperature of turnouts with various levels of bulk.

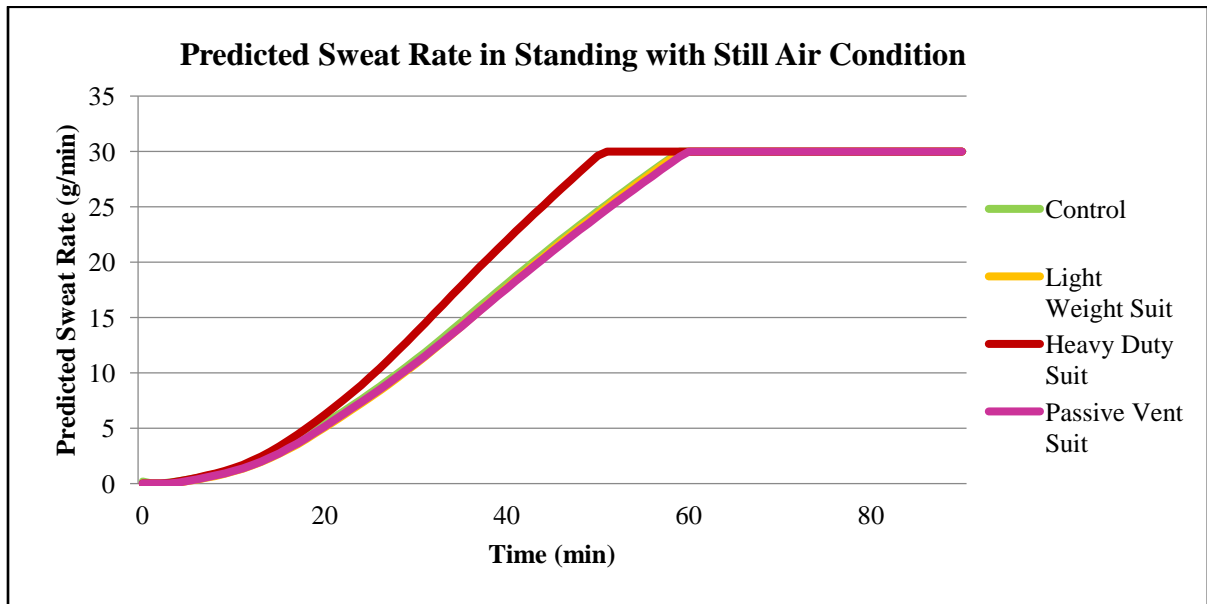


Figure C-2. Predicted sweat rate of turnouts with various levels of bulk.

Appendix D: Predicted Physiological Responses of Modular Approach Suits

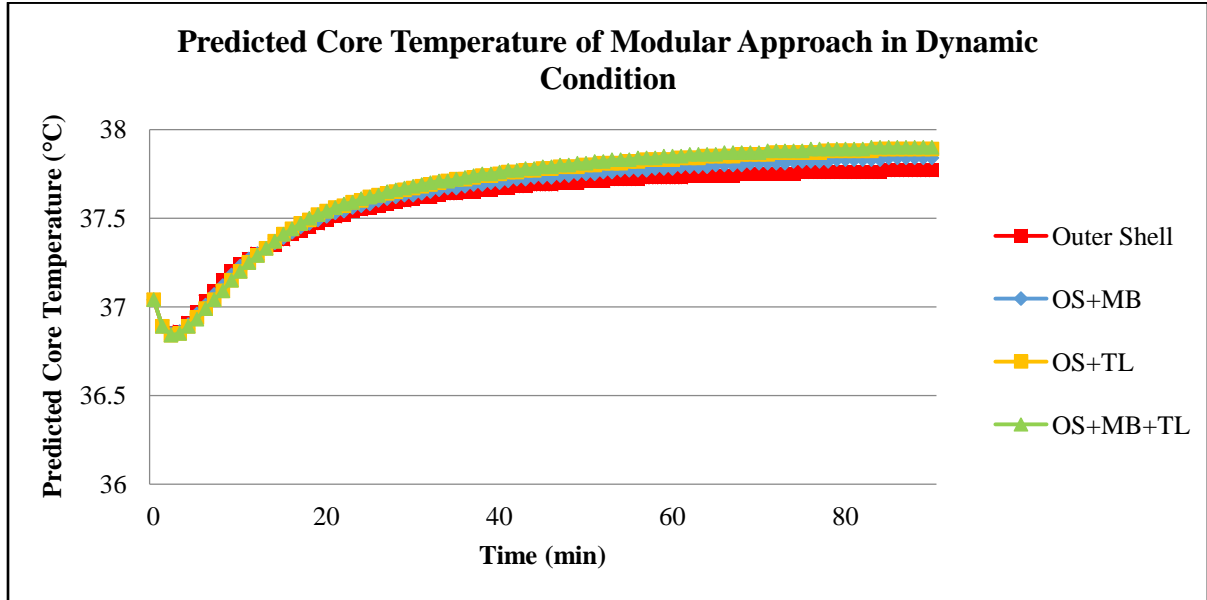


Figure D-1. Predicted core temperature of modular suits in walking with wind test condition.

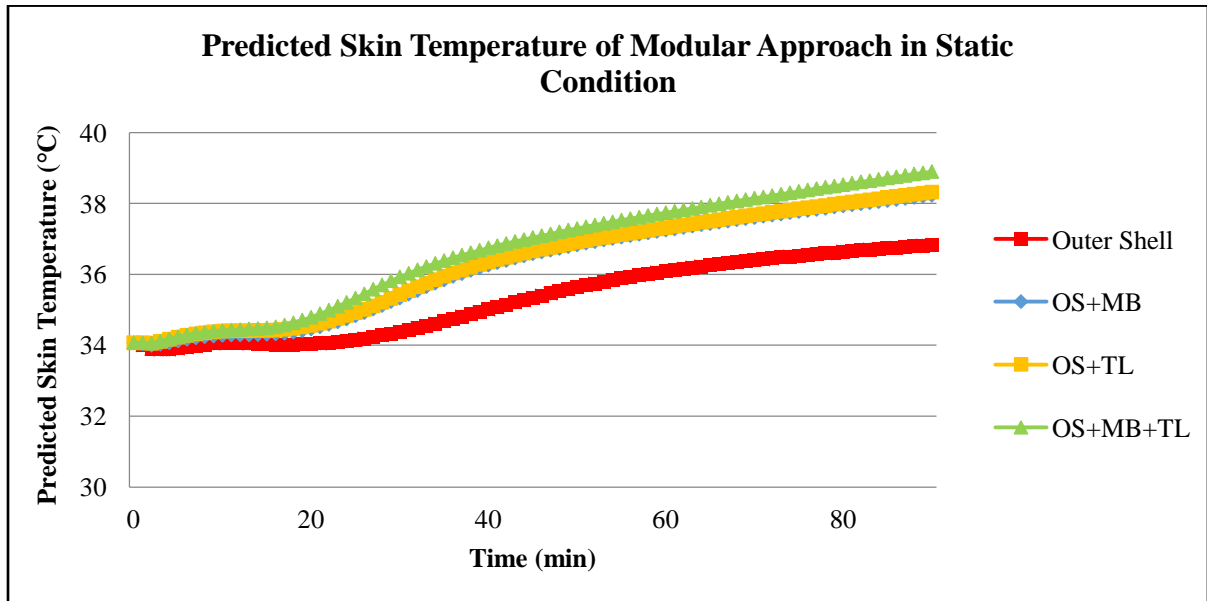


Figure D-2. Predicted skin temperature of modular suits in standing with still air test condition.

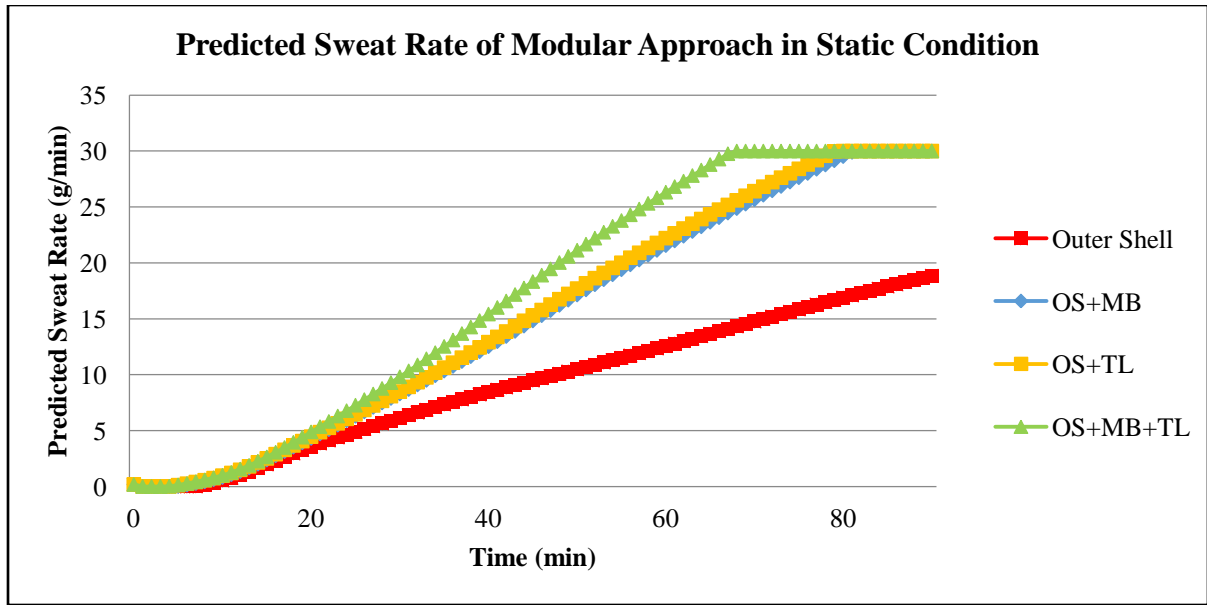


Figure D-3. Predicted sweat rate of modular suits in standing with still air test condition.

Appendix E: Predicted Manikin THL Diagrams in 35°C/35%RH Environment

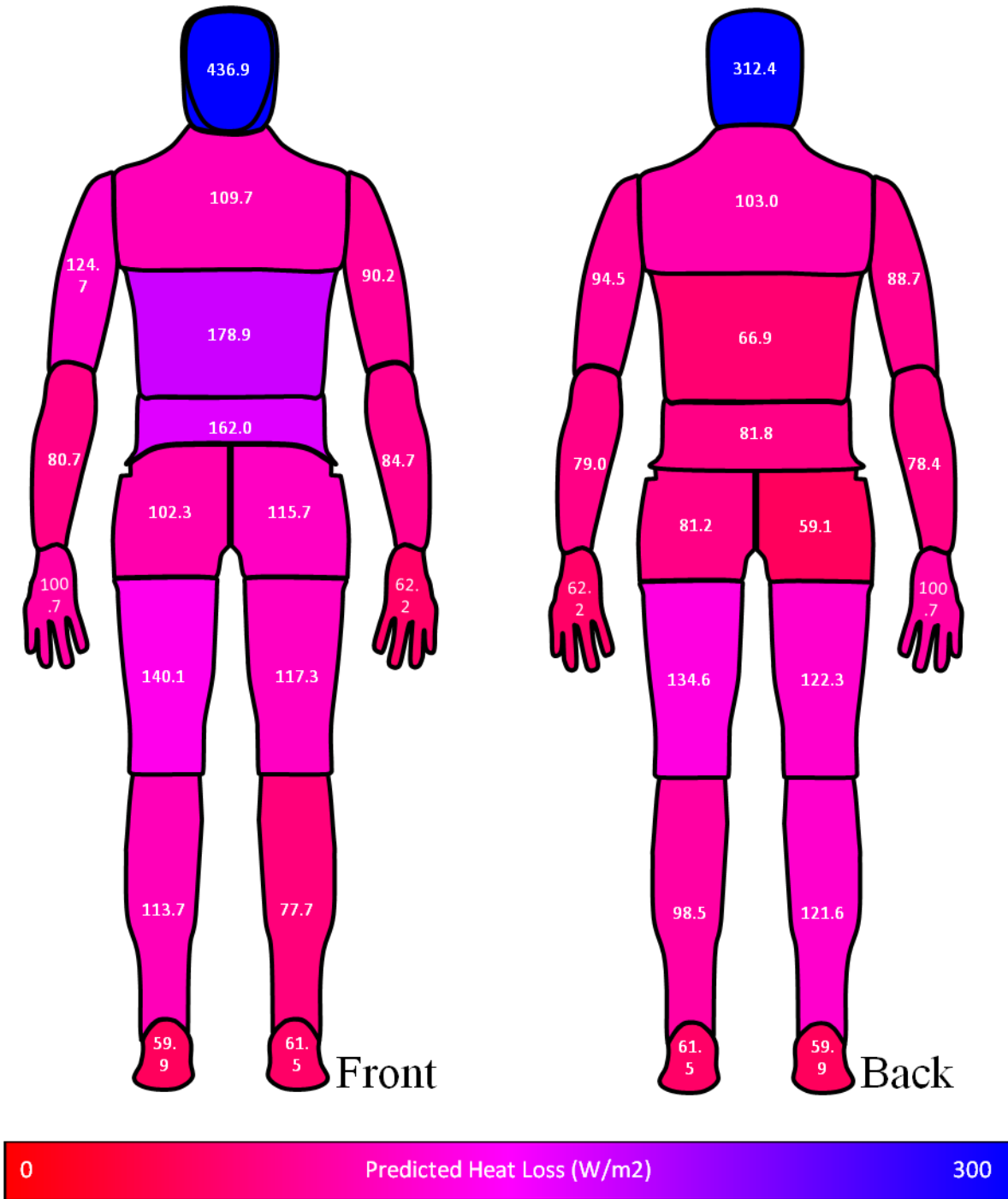


Figure E-1. Control turnout THL in walking with wind test condition.

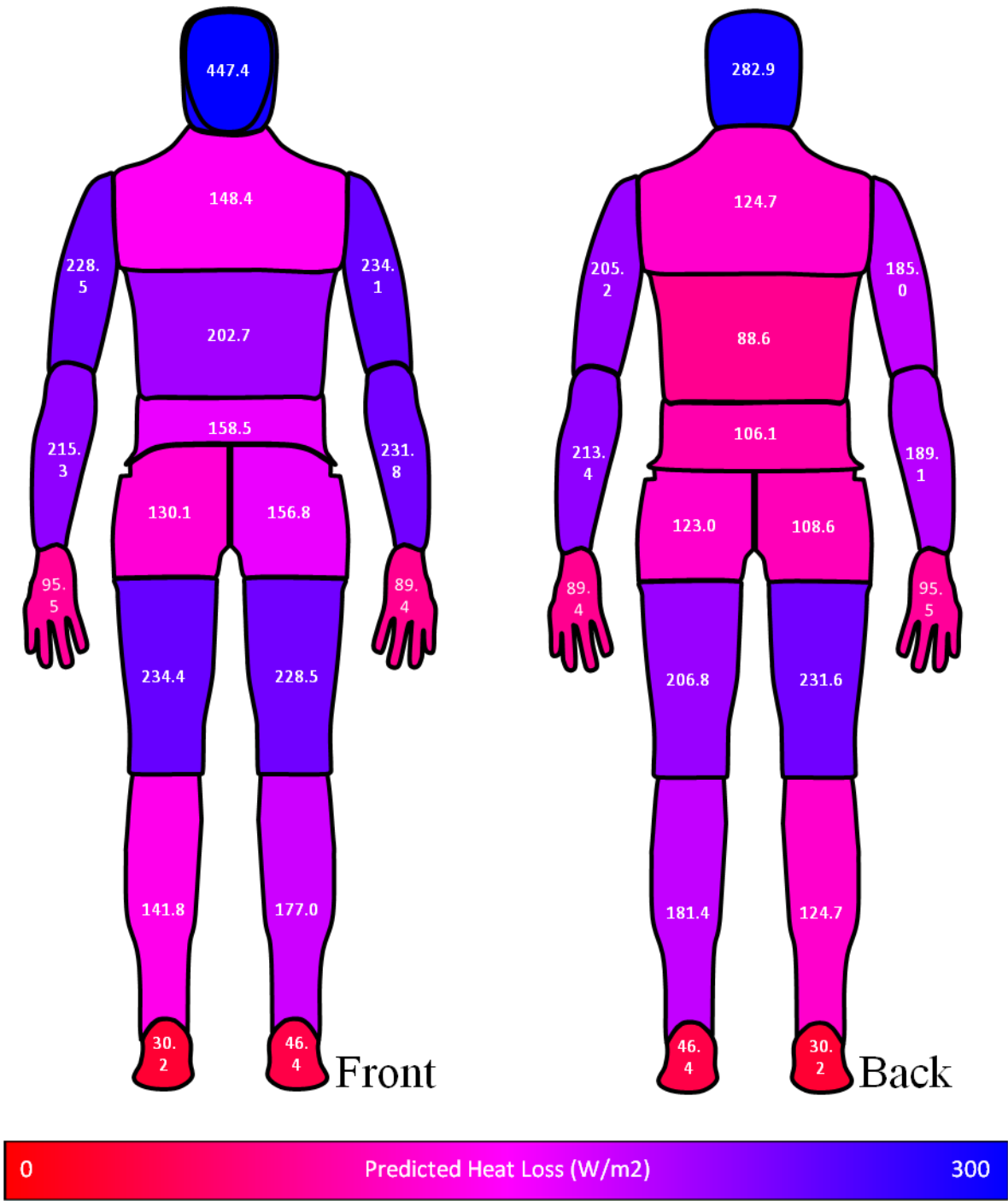


Figure E-2. USAR prototype turnout THL in walking with wind test condition.

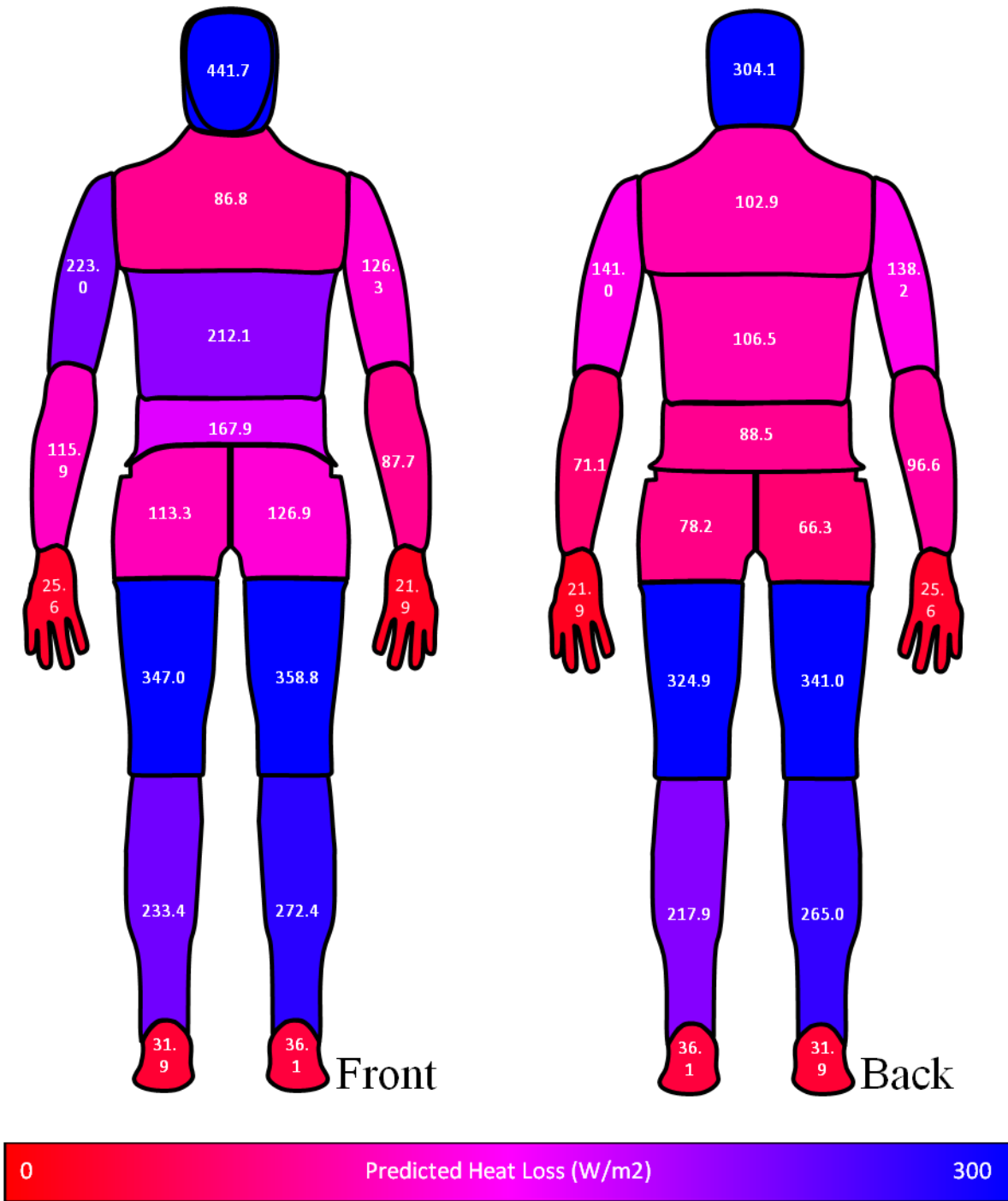


Figure E-3. Venting prototype turnout THL in walking with wind test condition.

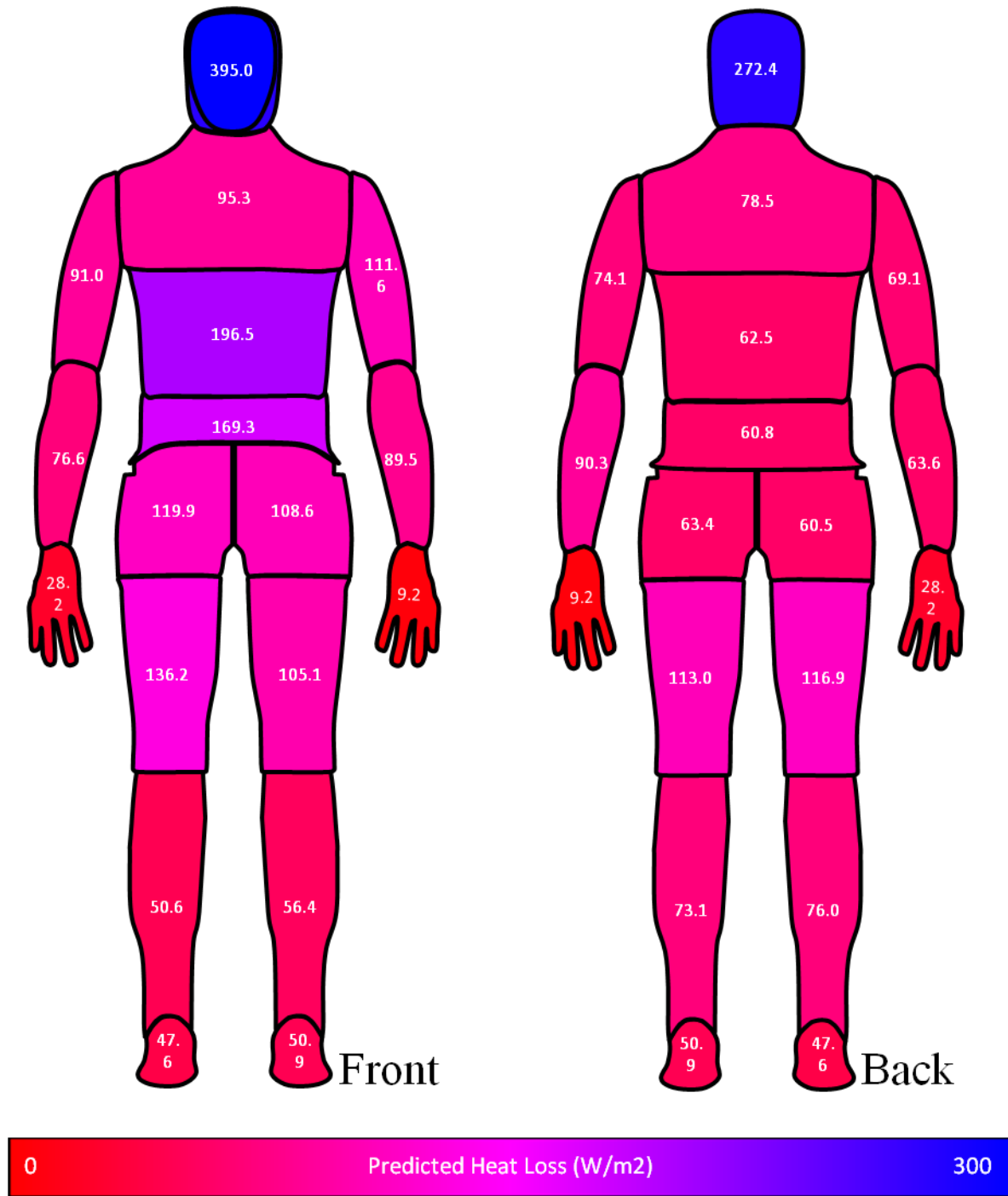


Figure E-4. Stretch prototype turnout THL in walking with wind test condition.

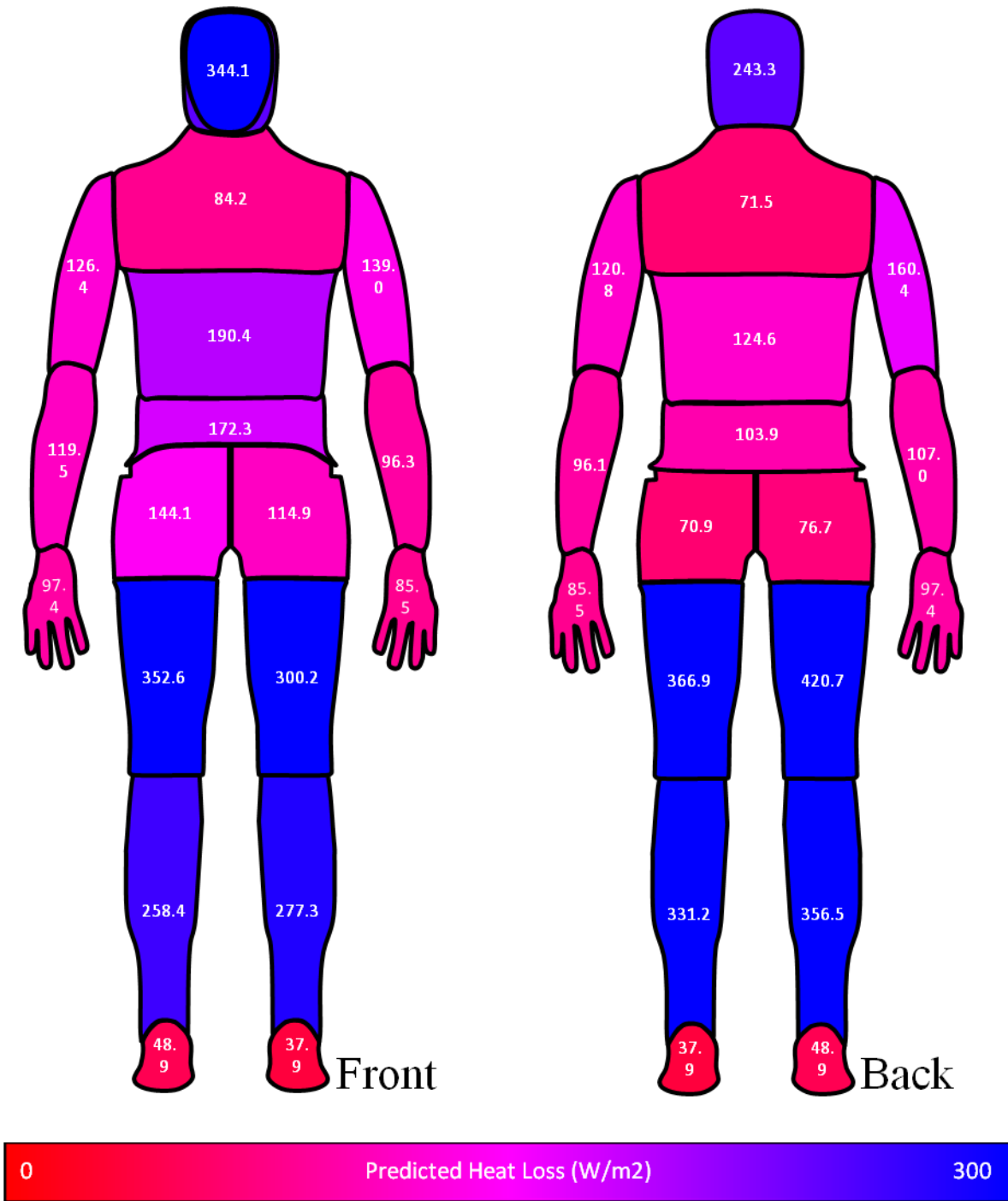


Figure E-5. Revolutionary prototype turnout THL in walking with wind test condition.

Appendix F: Predicted Physiological Responses of Prototype Suits in Static Test Condition

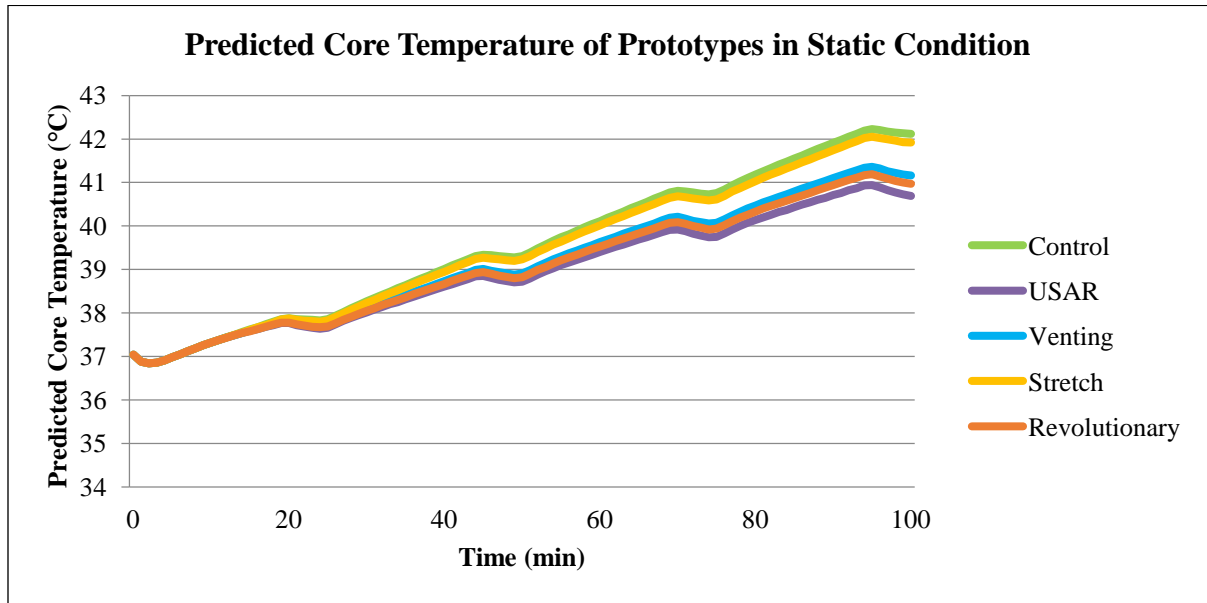


Figure F-1. Predicted core temperature of prototype suits in standing with still air test condition.

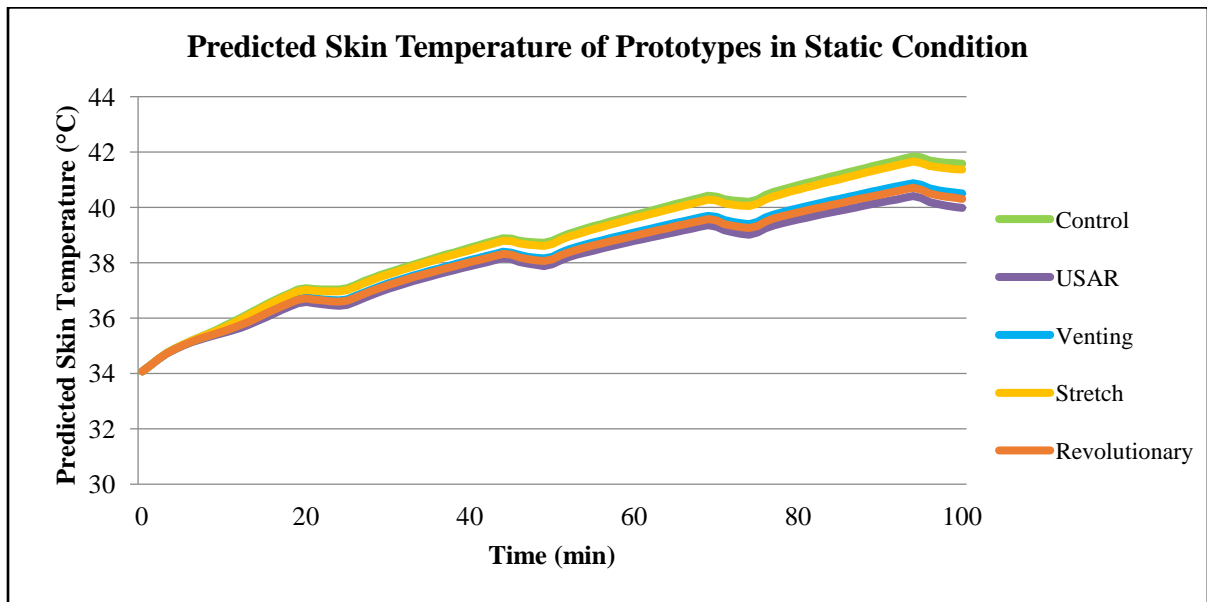


Figure F-2. Predicted skin temperature of prototype suits in standing with still air test condition.

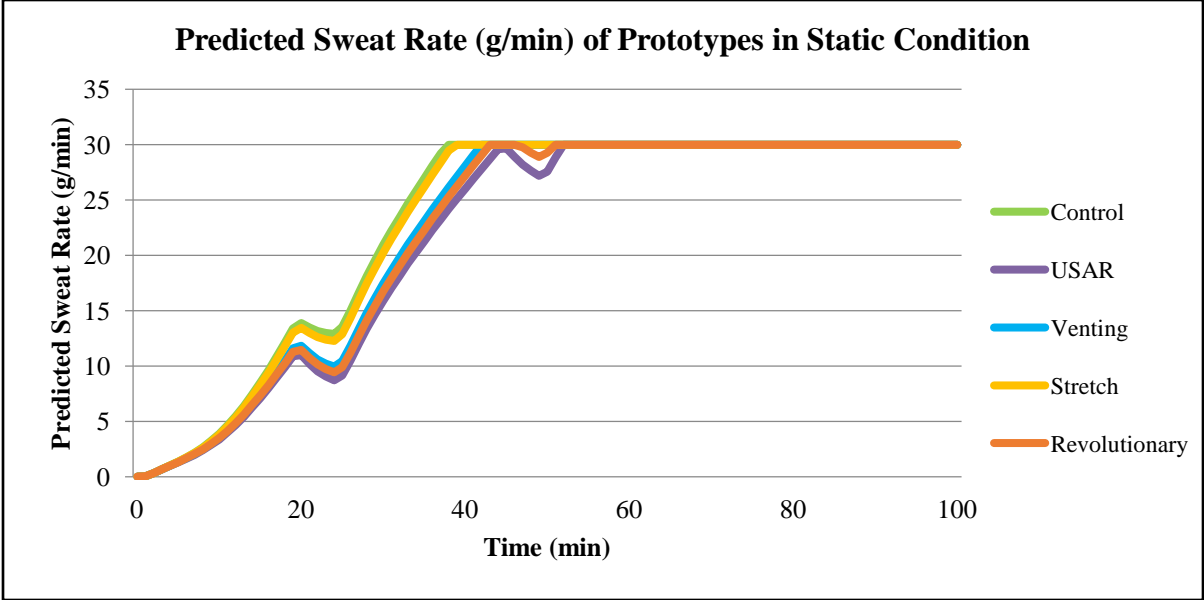


Figure F-3. Predicted sweat rate of prototype suits in standing with still air test condition.

Appendix G: Subjective Rating Scales

Rating of perceived exertion (Borg 1982)

Question asked by the researcher:

“How do you perceive the exercise at this moment?”

Rating	
6	
7	Extremely light
8	
9	Very light
10	
11	Light
12	
13	Somewhat hard
14	
15	Hard
16	
17	Very hard
18	
19	Extremely hard
20	

Perceived comfort scale (ISO 10551, 2001)

Question asked by the researcher:

“How do you perceive your whole body comfort at this moment?”

Rating	
0	Comfortable
1	Slightly uncomfortable
2	Uncomfortable
3	Very uncomfortable
4	Extremely uncomfortable

Temperature sensation scale (ISO 10551, 1995)

Question asked by the researcher:

“How do you perceive your whole body temperature at this moment?”

Rating	
+4	Very hot
+3	Hot
+2	Warm
+1	Slightly warm
0	Neutral
-1	Slightly cool
-2	Cool
-3	Cold
-4	Very cold

Appendix H: Physiological Wear Trial Testing Checklist and Tabular Protocol

AFG Modern Turnout Wear Trial

Subject ID:	Date:	Trial Time:	Suit:	90% Max HR:
-------------	-------	-------------	-------	-------------

At Least 24 Hours Before

<input type="checkbox"/>	Activate and Deliver Core Temperature Pill	<input type="checkbox"/> Activated By: <input type="checkbox"/> Delivered By: <input type="checkbox"/> Delivered On:
<input type="checkbox"/>	Confirm Subject's Scheduled Day/Time	<input type="checkbox"/> Date:_____ Time:_____ <input type="checkbox"/> Confirmed By:
<input type="checkbox"/>	Set Aside Garment and Accessories	<input type="checkbox"/> Heart Rate Monitor Straps (2) EquiVital Size:_____ <input type="checkbox"/> Polar Heart Rate Watch:_____ <input type="checkbox"/> Skin Temperature Patches (4) Neck:_____ Back:_____ Hand:_____ Shin:_____ <input type="checkbox"/> Socks <input type="checkbox"/> Boxer Briefs: _____ <input type="checkbox"/> Shorts: _____ <input type="checkbox"/> T-Shirt: _____ <input type="checkbox"/> Suit: _____ <input type="checkbox"/> Helmet Size: _____ <input type="checkbox"/> Gloves <input type="checkbox"/> Ensemble Weight: _____ <input type="checkbox"/> Shoes Weight: _____ <input type="checkbox"/> Humidifiers Filled <input type="checkbox"/> Tape <input type="checkbox"/> Duck Tape <input type="checkbox"/> Towels <input type="checkbox"/> SEMs Charging <input type="checkbox"/> Scale Available
<input type="checkbox"/>	Collect and Charge Team Equipment	

		<input type="checkbox"/> Walkie Talkies <input type="checkbox"/> Timers <input type="checkbox"/> Camera <input type="checkbox"/> Clipboards with Ratings/Scales <input type="checkbox"/> Snacks and Water (in chamber) <input type="checkbox"/> Water Weight: _____ <input type="checkbox"/> Computers Set Up <input type="checkbox"/> Anemometers (2)
<input type="checkbox"/>	Chamber and Habituation Area Ready	<input type="checkbox"/> Checked By:
<input type="checkbox"/>	EquiVital and Polar Software Functional	<input type="checkbox"/> Confirmed By:
<input type="checkbox"/>	EMTs will be Present	<input type="checkbox"/> Confirmed By:

Before Subject Arrival		
<input type="checkbox"/>	Habituation Room is Set Up	<input type="checkbox"/> 24°C (75.2°F); 50% RH; WBGT 20°C <input type="checkbox"/> Extra SEMs & HR Straps Available <input type="checkbox"/> Chairs, Tables, etc.
<input type="checkbox"/>	Environmental Chamber is Set Up	<input type="checkbox"/> Temp. & Humidity Set to 35°C (95°F) & 35% RH <input type="checkbox"/> EquiVital & Polar Ready <input type="checkbox"/> Dermal patches labeled <input type="checkbox"/> Humidifiers On <input type="checkbox"/> Water is provided <input type="checkbox"/> Treadmill @ 3% & 3.5 mph
<input type="checkbox"/>	Activate Dermal Temperature Patches and Assign SEM and Polar Heart Watch	<input type="checkbox"/> SEM #:_____ Polar Watch #:_____ <input type="checkbox"/> Neck:_____ Shoulder:_____ Shin:_____ Thigh:_____

<input type="checkbox"/>	Distribute Team Equipment	<input type="checkbox"/> Walkie Talkies <input type="checkbox"/> Timers <input type="checkbox"/> Camera <input type="checkbox"/> Clipboards with Ratings/Scales
<input type="checkbox"/>	EMTs are Present	<input type="checkbox"/> Pre/Post Exposure Questionnaire <input type="checkbox"/> Thermometer <input type="checkbox"/> Arrived at: _____

Upon Subject Arrival

<input type="checkbox"/>	Subject Dons Undergarments and Accessories	<input type="checkbox"/> Boxer Briefs <input type="checkbox"/> Shorts <input type="checkbox"/> T-Shirt <input type="checkbox"/> Sock(s) <input type="checkbox"/> Heart Rate Monitor Straps (2) <input type="checkbox"/> Polar Heart Monitor Watch
<input type="checkbox"/>	Checked Out by EMTs	<input type="checkbox"/> Pre Exposure Section Complete
<input type="checkbox"/>	Protocol Brief (if necessary)	<input type="checkbox"/> Subject's Questions are Answered
<input type="checkbox"/>	Subject Enters Habituation Room for 60 Minutes @ 24°C; 50% RH; 20°C WGBT)	<input type="checkbox"/> Entry Time: _____ <input type="checkbox"/> Timers Started
<input type="checkbox"/>	Verification of Core Temperature Pill	<input type="checkbox"/> Present – Pill #: _____ <input type="checkbox"/> Wearing Orange Wrist Band <input type="checkbox"/> Time Taken: _____ <input type="checkbox"/> Absent – Action Taken:
<input type="checkbox"/>	Don all Additional Sensors	<input type="checkbox"/> SEM <input type="checkbox"/> Dermal Temperature Patches

<input type="checkbox"/>	Weigh Subject in Boxer Briefs, Heart Rate Monitor Straps, SEM, Dermal Temperature Patches, and Polar Watch	<input type="checkbox"/> Subject Weight: _____ Note Maximum Heart Rate of: _____
<input type="checkbox"/>	Don Assigned Test Garment and Accessories	<input type="checkbox"/> Socks <input type="checkbox"/> Shorts <input type="checkbox"/> T-Shirt <input type="checkbox"/> Suit: _____ <input type="checkbox"/> Tennis Shoes <input type="checkbox"/> Gloves: _____ <input type="checkbox"/> Helmet: _____ <input type="checkbox"/> Habituation Exit Time: _____

Submaximal Test Protocol		
<input type="checkbox"/>	Enter Environmental Chamber at Specified Climatic Condition	<input type="checkbox"/> Treadmill #: _____ <input type="checkbox"/> 3 % Incline; 3.5 mph <input type="checkbox"/> Walking Start Time: _____
<input type="checkbox"/>	<p>Instruct subject to sit and rest OR begin walking activity at time points detailed in the right column. Subject should unzip coat at beginning of rest and zip up coat at end of rest.</p> <p>Collect Ratings on Perceived Exertion, Perceived Comfort, and Temperature Sensation at 2 min., 10 min., 20 min., 30 min., 40 min., 50 min., 60 min., 70 min., 80 min., and 90 min. Time Points</p>	2 Minutes into Walk: _____ <input type="checkbox"/> Perceived Exertion: _____ <input type="checkbox"/> Perceived Comfort: _____ <input type="checkbox"/> Temperature Sensation: _____ 20 Minutes into Walk: _____ <input type="checkbox"/> Perceived Exertion: _____ <input type="checkbox"/> Perceived Comfort: _____ <input type="checkbox"/> Temperature Sensation: _____ <input type="checkbox"/> 20 min. rest 25 Minutes at end of Rest: _____ <input type="checkbox"/> Perceived Exertion: _____ <input type="checkbox"/> Perceived Comfort: _____ <input type="checkbox"/> Temperature Sensation: _____ <input type="checkbox"/> 25 min. active 45 Minutes into Walk: _____ <input type="checkbox"/> Perceived Exertion: _____ <input type="checkbox"/> Perceived Comfort: _____ <input type="checkbox"/> Temperature Sensation: _____

		<input type="checkbox"/> 45 min. rest 50 Minutes at end of Rest: _____ <input type="checkbox"/> Perceived Exertion: _____ <input type="checkbox"/> Perceived Comfort: _____ <input type="checkbox"/> Temperature Sensation: _____ <input type="checkbox"/> 50 min. active 70 Minutes into Walk: _____ <input type="checkbox"/> Perceived Exertion: _____ <input type="checkbox"/> Perceived Comfort: _____ <input type="checkbox"/> Temperature Sensation: _____ <input type="checkbox"/> 70 min. rest 75 Minutes at end of Rest: _____ <input type="checkbox"/> Perceived Exertion: _____ <input type="checkbox"/> Perceived Comfort: _____ <input type="checkbox"/> Temperature Sensation: _____ <input type="checkbox"/> 75 min. active 95 Minutes into Walk: _____ <input type="checkbox"/> Perceived Exertion: _____ <input type="checkbox"/> Perceived Comfort: _____ <input type="checkbox"/> Temperature Sensation: _____ <input type="checkbox"/> 95 min. rest 100 Minutes at End of Test: _____ <input type="checkbox"/> Perceived Exertion: _____ <input type="checkbox"/> Perceived Comfort: _____ <input type="checkbox"/> Temperature Sensation: _____ <input type="checkbox"/> 100 min. exit chamber
<input type="checkbox"/>	Cutoff Criteria	<input type="checkbox"/> Max Time of 100 Minutes <input type="checkbox"/> Core Temp Exceeds 39°C <input type="checkbox"/> Core Temp Rises 0.6°C in a min

		Period <input type="checkbox"/> Max Heart Rate of _____ Reached <input type="checkbox"/> EMT or PI Terminates Test <input type="checkbox"/> Subject Terminates Test b/c: _____
<input type="checkbox"/>	Remove Test Garment and Accessories	<input type="checkbox"/> Everything Removed Except Boxer Briefs and Meas. Devices
<input type="checkbox"/>	Towel Off and Weigh Subject	<input type="checkbox"/> Towel Off <input type="checkbox"/> Subject Weight: _____ <input type="checkbox"/> Tennis Shoes Weight: _____
<input type="checkbox"/>	Remove all Sensors Except Heart Rate Monitor Straps and Keep Them Together Unless being Used for Next Session	<input type="checkbox"/> Sensors Placed or Given to: _____
<input type="checkbox"/>	Offer Water, Snacks, and Shower	<input type="checkbox"/> Subject is Recovered
<input type="checkbox"/>	Checked Out by EMTs	<input type="checkbox"/> Post Exposure Questionnaire Completed
<input type="checkbox"/>	Stop Polar Heart Rate Watch	<input type="checkbox"/> Stopped

After Test Completion		
<input type="checkbox"/>	Immediately After Session Completion	<input type="checkbox"/> Ensemble Weight: _____ <input type="checkbox"/> Water Weight: _____ <input type="checkbox"/> Confirm Polar Watch has Been Stopped <input type="checkbox"/> Clean Skin Temperature Patches
<input type="checkbox"/>	At End of the Day	<input type="checkbox"/> Anemometers (2) <input type="checkbox"/> SEM <input type="checkbox"/> Polar Watch Data <input type="checkbox"/> Laundry

PRE-TRIAL:

POST-TRIAL:

SUBJECT WEIGHT: _____

SUBJECT WEIGHT: _____

*Includes subject with boxer briefs, patches, monitors, straps, and polar watch

ENSEMBLE WEIGHT: _____

ENSEMBLE WEIGHT: _____

*Includes turnout, gloves, helmet, t-shirt, shorts, and socks

TENNIS SHOE WEIGHT: _____

TENNIS SHOE WEIGHT: _____

WATER BOTTLE WEIGHT: _____

WATER BOTTLE WEIGHT: _____

*Includes four water bottles given to subjects for consumption during protocol

Tabular Protocol

Step	Time	Description
1	Before Arrival	Ingest Core Temperature Pill
2	Arrival	Subjects arrive
3	15 minutes	Verify active pill and wristband
4		Complete pre-test questionnaire
5		Subject dresses in assigned underwear, shorts, t-shirt and socks
6	60 minutes	Subject enters controlled chamber to sit and rest for 60 minutes
7		EMT takes blood pressure 45 minutes into stabilization hour
8		EMT takes pulse 45 minutes into stabilization hour
9		EMT takes body temperature 45 minutes into stabilization hour
10		Skin temperature sensors placed on subject
11		Subject dons heart rate monitoring strap
12		Record weight of subject
13		Subject dons test ensemble
14	Protocol time Begins	Enter controlled chamber
15		Subject starts walking on treadmill
16	100 minutes	Perceived ratings taken (2 minutes)
17		Seated rest period; perceived ratings taken (20 minutes)
18		Perceived ratings taken; Subject resumes walking (25 minutes)
19		Seated rest period; perceived ratings taken (45 minutes)
20		Perceived ratings taken, subject resumes walking (50 minutes)
21		Perceived ratings taken; seated rest period (70 minutes)
22		Perceived ratings taken; Subject resumes walking (75 minutes)
23		Seated rest period; perceived ratings taken (95 minutes)
24		Perceived ratings taken (100 minutes)
25	Protocol time Ends	Concludes testing period
26	10 minutes	Subject takes post-test questionnaire
27		Subject doffs the test ensemble
28		Subject is weighed
29		Remaining instrumentation removed
30	15 minutes	Subject proceeds to dressing room to ready themselves for the remainder of their day
31		EMT administers post-test questionnaire
32		EMT take and record blood pressure
33		EMT take and record pulse
34		EMT take and record body temperature
35		EMT clears the Subject to leave

Appendix I: Skin Temperature Data by Measurement Location

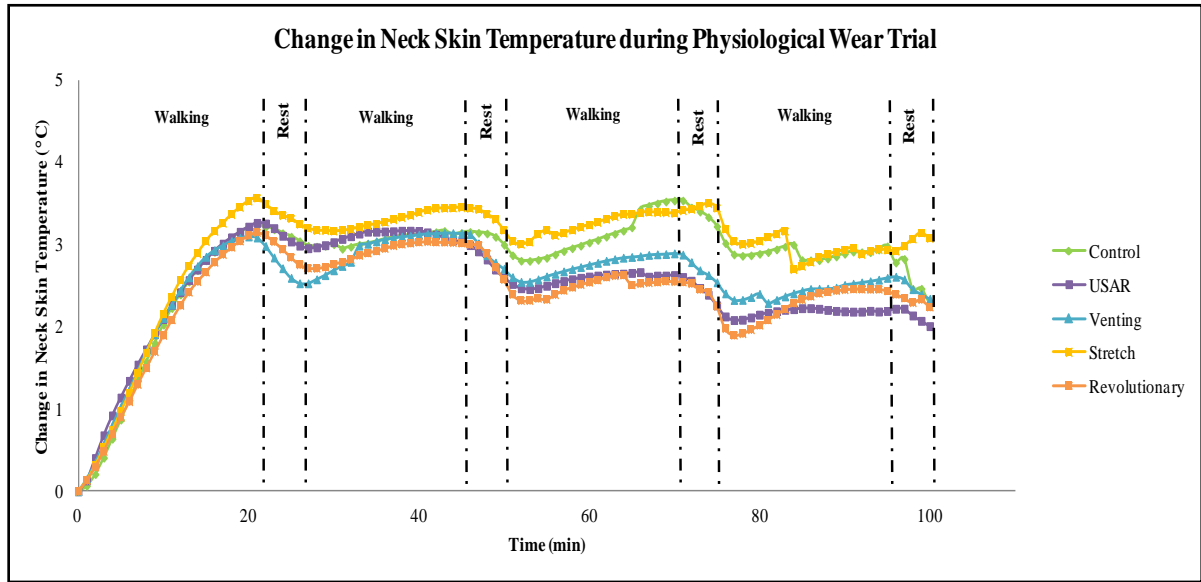


Figure I-1. Change in neck skin temperature for each prototype suit in physiological human wear trial.

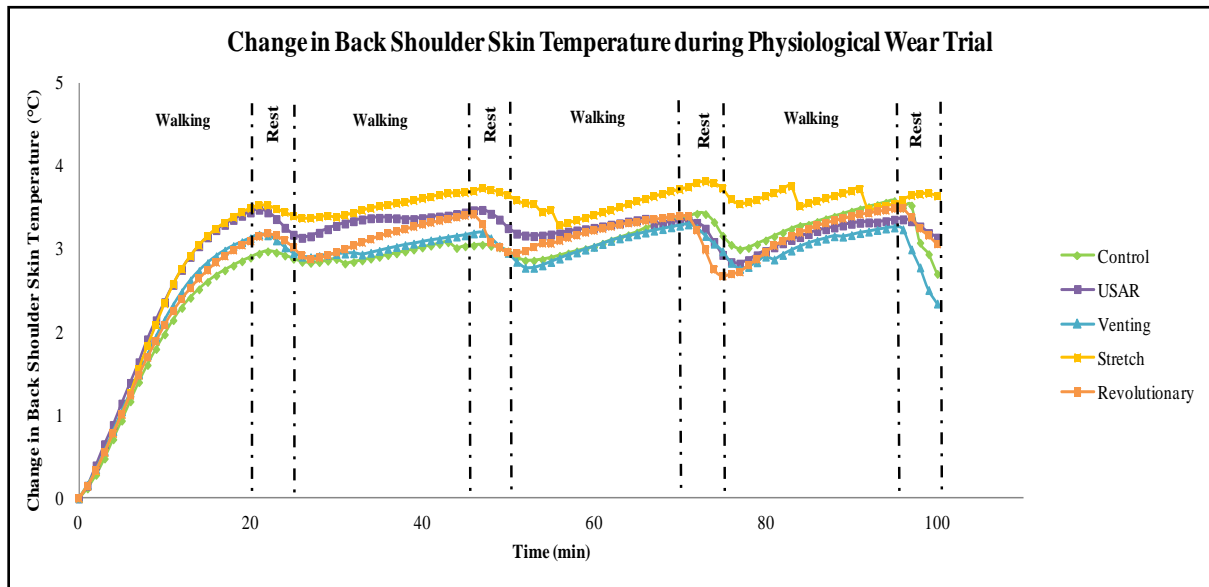


Figure I-2. Change in back shoulder skin temperature for each prototype suit in physiological human wear trial.

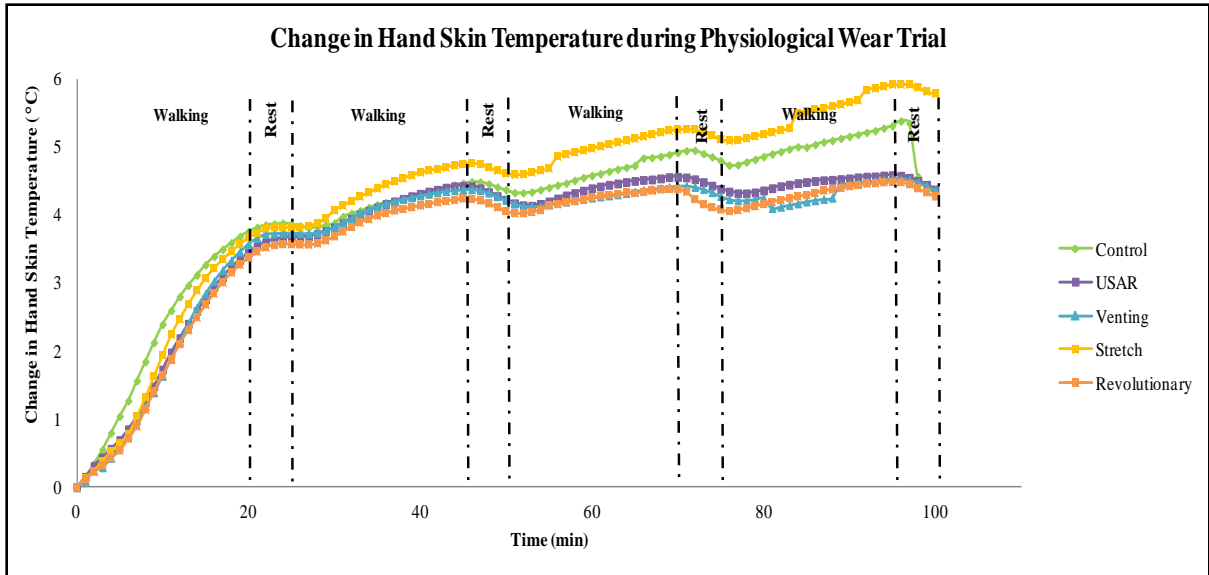


Figure I-3. Change in hand skin temperature for each prototype suit in physiological human wear trial.

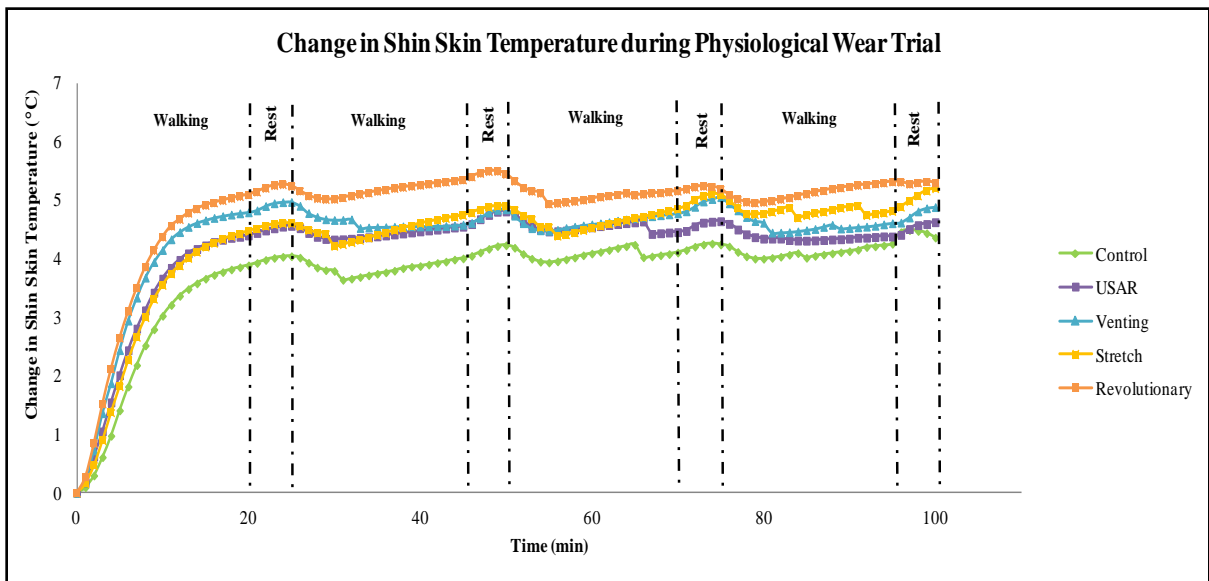


Figure I-4. Change in shin skin temperature for each prototype suit in physiological human wear trial.