# ABSTRACT

ROSS, KEVIN ANDREW. **Evaluation of an Instrumented Sweating Manikin for Predicting Heat Stress in Firefighters' Turnout Ensembles.** (Under the direction of Roger Lee Barker)

This research studies relationships between measurements of heat loss through firefighter turnout ensembles measured using a sweating thermal manikin and a guarded sweating hot plate. Measurement techniques and results are compared. These two measures of heat loss are also compared on their ability to explain thermal heat stress. The assessments of thermal heat stress were provided in a report from an earlier physiological study where human responses were evaluated during wear trials of firefighter protective gear.

The focus of this research was on the role of the instrumented sweating manikin as a supplemental tool in predicting heat stress. Its human form makes it a logical intermediary tool between a flat skin model (hot plate) and human subject testing. Thus, it was decided to investigate its role by using it to evaluate six firefighter turnout ensembles where there was existing data available for comparison to both hot plate and physiological test results.

The results of this study indicate that sweating thermal manikin measurements provide a fuller explanation and prediction of heat stress assessments in physiological wear trials than provided by a sweating hot plate. This is attributed to the ability of manikin tests to evaluate the effects of garments' insulating air layers and the contribution of clothing design features to the total thermal burden. This research provides insights into the use of instrumented manikins as research tools and as means of providing information useful for predicting and explaining the results of physiological wear trials of firefighter protective clothing. Thermal manikins are also shown to be valuable tools for evaluating the distribution of heat loss through different areas of protective gear.

**EVALUATION OF AN INSTRUMENTED SWEATING MANIKIN FOR PREDICTING HEAT STRESS IN FIREFIGHTERS' TURNOUT ENSEMBLES**

by

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BIOGRAPHY

Kevin Andrew Ross was born February 11, 1981 to Donald and Joanne Ross in Riverside, California. He spent most of his youth growing up with his brother and sister in Wilmington, North Carolina where he attended elementary and middle school before finally graduating from John T. Hoggard High School in 1999.

Later in 1999, Kevin moved to Raleigh, North Carolina to begin life as a student at North Carolina State University. As a Textile Engineering student, Kevin kept busy at school with his studies and pursuit of a Spanish Minor. Outside of class, Kevin did a little bit of everything including working as a lifeguard, playing in various soccer leagues, getting involved with the Delta Kappa Phi Textile Fraternity and other organizations, trying to play the guitar, and cheering for the Wolfpack.

In 2001, Kevin was inducted into the Phi Kappa Phi National Honor Society and in 2002 he spent seven weeks in Peru with a group of fellow students studying Spanish. In 2003, Kevin graduated Magna Cum Laude in Textile Engineering with a minor is Spanish. After earning an Engineering Intern Certification and applying to graduate school, he took several months off of school to work as a Project Engineer Intern for Parkdale Mills. In the fall of 2003, Kevin continued his education at NCSU pursuing a Masters of Science in Textile Engineering. Kevin was fortunate to work on a very interesting and important project, one of the first funded by the Department of Homeland Security. As part of a research team at NCSU, Kevin helped in the development of a new firefighter turnout suit designed to be resistant against chemical and biological agents. Kevin will graduate with the Degree of Master of Science on May 13, 2006.

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# Chapter 1: Introduction

## 1.1 Purpose

Firefighting is a dangerous job and fatalities are an unfortunate, but inevitable part of the job. Since the United States Fire Administration (USFA) started tracking annual fatalities and their nature almost thirty years ago, there have been some disturbing trends that have warranted much research within the industry. During the last fifteen years, roughly 50% of the approximate 100 annual on-duty firefighter fatalities in the United States are attributed stress or overexertion [1]. This led the National Fire Protection Agency (NFPA) to form a committee on heat stress which was tasked with organizing research to address the topic.

The research led to the development of the Total Heat Loss (THL) test which was included as part of the NFPA 1971 standard for structural firefighting. The test uses a guarded sweating hot plate in order to determine the thermal and evaporative resistances of the garment materials. Since the development of the test, several studies have investigated its ability to predict physiological responses in controlled wear trials using human subjects. Though different studies resulted in different conclusions, the THL test continues to be the standard for measuring the heat stress potential of turnout gear.

## 1.2 Research Objectives

The basic objective of this research was to investigate how the sweating thermal manikin could be used as an intermediate tool to bridge the gap between the sweating hot plate and physiological testing. By testing the garments in the most realistic wearing conditions as possible, it may be possible to achieve more complete information as to how a garment could be expected to perform when worn in similar conditions in a physiological wear trial. By comparing the hot plate, manikin, and physiological results I hope to validate the usefulness of the manikin for heat stress modeling and establish whether or not it can yield any beneficial information beyond that already capable by use of the sweating hot plate.

Specific major objectives and tasks of this research include:

1. Determine the relationship between heat transfer data (thermal resistance, evaporative resistance, and Total Heat Loss) measured by the sweating manikin and the hot plate
    a. Measure the thermal and evaporative resistances of various turnout ensembles
    b. Calculate predicted total heat loss on the manikin for standard hot plate conditions and physiological study conditions
2. Determine how heat transfer data measured on the manikin and hot plate compare with available physiological data
3. Identify any potential advantages the manikin offers over the hot plate in measuring heat stress in firefighter gear

Achievement of these objectives will highlight differences between the sweating hot plate and sweating manikin in their ability to predict physiological responses. They also may well guide further analysis that can be done to identify what other possible advantages the sweating manikin may offer in predicting heat stress. Finally, they should serve as a benchmark to guide further research into the predictive capabilities of both the sweating manikin and the sweating hot plate.

## Chapter 2: Literature Review

### 2.1 Need for Research

The United States Fire Administration (USFA) has tracked and analyzed annual firefighter deaths for almost thirty years [2]. According to their reports, there have already been 64 on-duty U.S. firefighter fatalities this year (1/1/2005 to 7/31/2005) [3]. Of these fatalities, 38 (59.3%) have been classified as due to stress or overexertion. The ultimate cause of death in these fatalities has been a heart attack in 34 of the cases, cerebro-vascular accident (CVA) in another 2 cases, heat exhaustion in 1 case, and trauma in 1 case [3]. Often, during firefighting operations, heat stress and/or dehydration compromise the pumping of the heart leading to cardiovascular strain. This strain can be accompanied by insufficient blood flow to the heart and lead to chest pains or a heart attack [4]. The nature of these fatalities varies somewhat each year, but the overall numbers appear to be consistent with that which has been reported in the past.

From 1986 to 2003, an average 46.1% of on-duty firefighter fatalities were attributed to stress or overexertion [3, 5-23][1]. During each of these years, stress or overexertion was the number one cause of on-duty fatalities, each year comprising anywhere from 35.6% to 54.1% of the total on-duty fatalities [3, 5-23].[2] Stress, including overexertion, has also been reported to make up a substantial amount of non-fatal

[1] All numbers and calculations reflect the reported statistics for the annual report released for that year. Some information has been modified during later years when additional fatalities were reported.

[2] Statistics do not include the hundreds of firefighters fatalities that occurred on the September 11, 2001 attack on the World Trade Centers

firefighter injuries in the past [24]. Figure 2.1 shows the reported number of on-duty firefighter fatalities from 1977 to 2003[3][22].

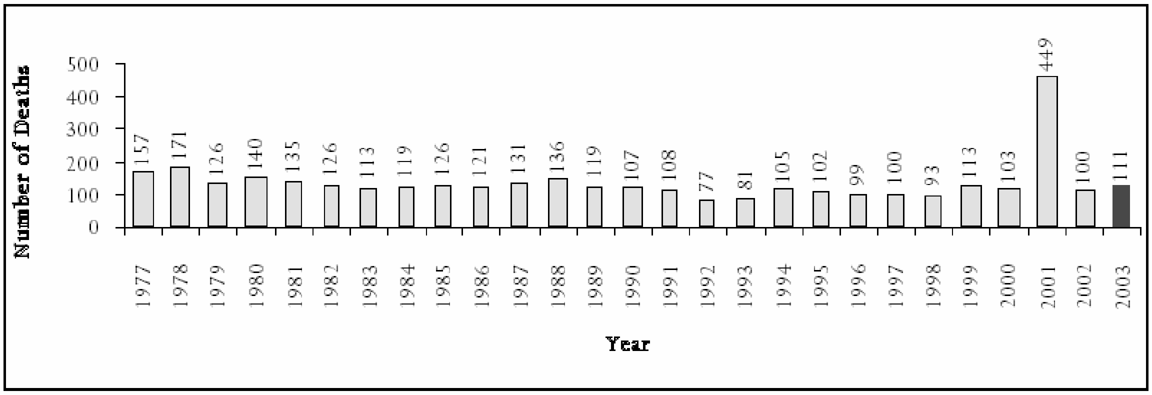



**Figure 2.1: On-Duty Firefighter Fatalities (1977-2003)**

The number of overall fatalities appears to be considerably lower in the latter 13 years in Figure 2.1 (since 1990 and excluding 2001) compared with the first 13 years (from 1977 to 1989). However, though the overall number of deaths seems to have decreased since 1977, there is little evidence to suggest that heat stress is any less of an issue. In fact, advancements in protective clothing that have been aimed at preventing burn injuries seem to have had a negative impact on heat stress [25]. Last year, the number of fatalities attributed to heat stress was 66, making up 56.4% of all on-duty fatalities reported [3].

On December 15, 2003, President Bush signed into law the Hometown Heroes Survivors Benefit Act of 2003 [2]. The law, Public Law 108-182, will undoubtedly have an affect on both the number of overall fatalities and percent of which are owed to stress

[3] Includes the fatalities that occurred on the September 11, 2001 attack on the World Trade Centers

or overexertion. The law declares that a firefighter will be considered to have died on-duty if he dies from a heart attack or stroke where his initial signs of illness were observed either on-duty or within 24 hours after the end of a tour of duty in which he had engaged in non-routine, stressful or strenuous physical activity [2]. The increase in total fatalities reported by the USFA, because of the new definition of on-duty fatality by stroke or heart attack, is estimated to be between 6 and 8% [2]. This is not surprising since heart attacks (always overwhelmingly number one) and stokes (CVA) have consistently been the leading causes of fatalities that are attributed to stress or overexertion [3, 5-23]. This means that according to how we view things now, the number of heat- and stress- related deaths reported in the past is significantly lower than actually occurred. The need to address this issue of heat- and stress- related deaths with a considerable amount of research is obvious.

### 2.1.1 Heat Stress and Heat Strain

Heat stress is the "net heat load to which a worker may be exposed…" as defined by the American Conference of Government Industrial Hygienists (ACGIH) [26]. One incurs a risk due to heat stress whenever the body gains heat at a faster rate than they can lose it. Clothing, because it traps body heat, means there can be a risk of heat stress even when working in the cold [27]. Wearing protective clothing particularly limits the amount of heat the body can lose by convection, radiation and evaporation, thus placing workers such as firefighters at greater risk of heat stress [28]. A Finish study in 1992 involving firefighters performing typical firefighting tasks resulted in the firefighters reaching core temperatures up to 41.4ºC indicating the true risk of heat-related illnesses or even death from heat stress in these realistic firefighting scenarios [29]. Reaching temperatures this high is especially dangerous because once the body temperature rises above about 40ºC the mechanisms that normally regulate body temperature around 37ºC stop working [28]. If the body is unable to lose heat, even small amounts of heat gained from working can cause heat strain within 30 minutes [2].

The ACGIH defines heat strain as "the overall physiological response resulting from heat stress." [26]. One way to consider it is according to its engineering analogy in which strain is the result of an imposed stress [30]. Failure to treat heat strain immediately can lead to a number of heat illnesses [26]. These illnesses include heat stroke (hyperthermia), heat exhaustion (heat prostration), heat cramps, heat rash (miliaria), transient heat fatigue, and fainting (syncope) [31]. Heat strain, when combined with the exertion of typical firefighting duties, can also lead to cardiovascular strain due to decreased stroke volume [32]. This is thought to be a leading cause of heart attack and a major concern of the firefighting industry [32]. It is also possible that other heat-related deaths are reported as heart attacks or strokes since these deaths are often a diagnosis of exclusion and misclassified as one of these two, more familiar causes [33].

### 2.1.2 Heat Stress Development in Firefighter Garments

Heat stress is a major concern for a variety of occupations, but is especially a risk for occupations where protective clothing is worn such as in firefighting. Firefighters' protective clothing both increases heat production and interferes with the body's ability to lose heat [34]. The weight, stiffness, and extra bulk at body joints all contribute to the turnout gear being an added metabolic burden in firefighting; wearing the complete ensemble with a Self Contained Breathing Apparatus (SCBA) typically increases heat production by about 30% over just the station uniform when performing the same task [34]. In addition to the extra work it entails, turnout gear also hampers the body's ability to thermoregulate. If the body cannot lose heat, it will store it and become at risk of contracting a heat illness. The heat balance of the body is usually described by some variation of the following general equation:

Store = heat production – heat loss = (metabolic rate – external work) – (conduction + radiation + convection + evaporation + respiration) [27].

Generally, conduction, radiation and convection are considered avenues of heat loss; however, in certain environmental conditions (such as may be present in firefighting), these can actually become avenues of heat gain [27]. The majority of the heat that is stored, however, is much more typically that which the body produces and is unable to release. When the body is working, active muscles require more energy and nutrients than at rest and so metabolic rate increases [27]. When the muscles burn these nutrients, some of the energy they contain is released outside the body as external work, but the majority of it is released in the muscle as heat [27]. So, in order to keep the body from storing heat and rapidly increasing in temperature, it must lose heat by conduction, radiation, convection, evaporation or respiration.

### 2.2 Heat Transfer

In order to combat heat stress, one must understand the relationship between the body, the clothing, and the environment and how they contribute to the development of heat stress. The first step in understanding this relationship is to understand the mechanisms of heat transfer which define this relationship.

#### 2.2.1 Dry Heat Transfer

Conduction only occurs where the body is in direct contact with another surface and usually plays a very minor role in heat loss from the body [27]. Convection is a much more significant avenue for heat loss provided that the ambient air is cooler than the skin [27]. Electro-magnetic radiation can also be a significant means of heat transfer if the surface temperature of the body is much different than the surface temperature of the objects in the environment [27]. The earliest and still much preferred method of characterizing heat transfer involving clothing is to lump conduction, convection and radiation into one term collectively known as dry heat transfer [35]. The clothing property associated with dry heat transfer is its insulation value and is effectively its resistance to dry heat transfer ($R_{ct}$) [35]. This value is in units of $K \cdot m^2/W$ and includes all layers of clothing from the skin to the environment, including boundary air layers [35]. Boundary air layers develop as a still air layer attached to outer surface of each material [27]. It can be up to 6 mm thick on either side of a material trapping up to 12 mm of still air for a single layer [27]. Air is highly insulative and thus the insulation value for a multilayer garment will be much higher than could be expected from adding the insulations of the material layers alone [27]. Another unit that is used within the industry to describe a garment's insulation is the clo unit. 1 clo equals 0.155 $K \cdot m^2/W$ [36]. In a normal indoor environment, 1-clo 'normal' indoor clothing is the amount which will allow man to properly balance the heat produced at rest plus that which is lost through evaporation from his skin or water from his lungs [35, 37].

### 2.2.2 Evaporative Heat Transfer

A garment's insulation is important in determining the heat loss ability of an individual; however, there is another unit that is, perhaps, a more important value when talking about heat stress in firefighter garments. With conduction, convection, and radiation often being avenues of heat gain during firefighting activities, heat loss by evaporation or through the lungs remain the only natural ways of passively cooling the body [38]. Heat loss through respiration occurs as one warms and moistens inspired air then releasing it to the environment; it can make up for up to 10% of the total heat production [27]. During firefighting, heat loss through respiration would mostly vary according to the rate at which one was breathing. Heat loss through evaporation, however, is a function of the garment materials and design. Firefighter turnouts, to be certified, are necessarily resistant to liquid flow [39]. Therefore, to evaporate through the firefighter garment, the sweat must travel through the garment's moisture barrier as a vapor [40]. This can significantly reduce the ability of the body to cool itself by evaporation since a phase change (latent heat of evaporation) must occur in order for the sweat to have any cooling properties. There has been much investigation as to whether there is a significant difference between garments that use moisture barriers which permit the transmission of vapor (breathable or semi-permeable garments) versus those which do not (non-breathable or impermeable garments). While some researchers have doubted that any noticeable differences would exist when worn in actual firefighting conditions, more recent studies have shown that in many cases physiological differences do exist [24, 34, 41-45]. At times, core body temperatures have been shown to be approximately 1.0 ºC lower when wearing breathable versus non-breathable garments [46]. The degree of breathability for a particular garment can be described in terms of its evaporative resistance ($R_{et}$ [=] kPa·m²/W) [47]. Another common way of expressing a garment's capability for evaporative heat transfer is by the permeability index ($i_m$). The permeability index is normalized against an ideal condition of minimal still air alongside the naked skin and can range from 0 (totally impermeable) to 1 (totally permeable) [37, 48]. It is often used in conjunction with the clo value, termed the Permeability Index Ratio (expressed as $i_m$/clo), to indicate the percentage of maximum possible evaporative cooling obtainable for a particular garment in a particular environment [34]. Actual evaporative cooling is therefore regulated by both the evaporative resistance and insulation of the clothing [34].

### 2.2.3 Environmental Conditions and Heat Transfer

Whether through dry or evaporative heat transfer, no heat can flow from the body to the environment if there is not a difference in either the temperature or vapor pressure between the skin and the outside air [34]. This concept is apparent as you consider the governing equations for evaporative and dry heat loss:

| | | |
|---|---|---|
| Dry Heat Loss = $(t_{sk} - t_a)/I_T$, where | $t_{sk}$ = | skin temperature, |
| | $t_a$ = | air temperature, and |
| | $I_T$ = | clothing insulation, including air layers |

| | | |
|---|---|---|
| Evaporative Heat Loss = $(p_{sk} - p_a)/R_T$, where | $p_{sk}$ = | skin vapor pressure, |
| | $P_a$ = | air vapor pressure, and |
| | $R_T$ = | clothing vapor resistance, including air layers [27]. |

It should also be apparent then, that when the ambient temperature is greater than the temperature of the skin (approximately 35 ºC), it is impossible to lose heat to the environment, and instead, one will begin to gain heat from the environment via dry heat transfer [34]. However, as long as the moisture concentration at the skin is higher than that in the environment, evaporative heat loss will be possible [27]. If the gradient is reversed however, loss of heat through sweating is impossible and the situation can be extremely stressful [27]. Generally, the relative humidity is a good indicator of how much moisture is in the air; however, it should be noted that moisture content and not relative humidity is the decisive factor. For a given relative humidity, air is able to hold more moisture at higher temperatures. Therefore, as long as the air temperature is less than the skin temperature, sweat can always evaporate from the skin, even at 100% relative humidity [27].

### 2.3 Combating Heat Stress

Whether dry or evaporative, the ability of the body to lose heat depends on a number of factors including climate, the task, the characteristics of the person involved, and the clothing [49]. Usually, one would not be able to manipulate the environment, so must either modify the person, the task, or the clothing [34]. Modifying the person or the task are possibilities that are exist, but often are issues of training, logistics, or practicality for the individual fire department [34]. Modifying the clothing is a job for scientists and engineers.

#### 2.3.1 Clothing Considerations

Firefighter clothing in its nature poses a number of challenges for its engineers. Its seemingly contradictory requirements include protection against flame and heat from penetrating the garment while still somehow allowing for some amount of heat to escape [39]. This heat loss must be accomplished by either a temperature gradient, or else evaporation, yet the garment must also protect the wearer from water and other liquids entering the garment [39]. Also, it must be quite durable, but still should allow for maximum flexibility and general ease of use [34, 39]. These requirements, set by the National Fire Protection Association (NFPA), are often a challenge to meet, but set important minimum performance standards for protecting our nation's first responders.

### 2.3.2 NFPA 1971 Standard

The NFPA 1971 Standard on Protective Ensemble for Structural Fire Fighting is the critical standard in the industry which specifies the minimum design, performance, certification requirements and test methods for structural protective ensembles including protective coats, protective trousers, protective coveralls, helmets, gloves, foot-wear, and interface components [39]. This standard lays out the certain design and performance requirements for the clothing that must be passed by the clothing manufacturers for all structural firefighting gear. The standard has many detailed specifications which must be passed, but there are three in particular which are particularly relevant when thinking about heat stress. These considerations which seem to be crucial elements in the discussion of heat stress and its development are the various aspects of garment design, the thermal protective performance (TPP) requirement on the composite, and the total heat loss (THL) requirement on the composite.

## 2.4 Firefighter Garments

The term garment, when referring to firefighter turnout gear, is defined as the coat, trouser, or coverall elements of the protective ensemble designed to provide minimum protection to the upper and lower torso, arms, and legs, excluding the head, hands, and feet [39]. Typically, the garment would consist of coats and trousers since coveralls are seldom seen in the industry. NFPA 1971 requires that each garment be constructed of an outer shell, a moisture barrier, and a thermal liner [39]. These could be manufactured as a single layer or multiple layers and an optional winter liner could be added as well. However, most turnout garments available today would consist of just the three required layers, each of them being a separate layer except that they may be attached at the seams. Oftentimes firefighters will choose a particular garment design that they like and then specify which materials they want used for each layer of the garment. Manufacturing companies likewise often specialize in the fabrication of a particular layer. This is all due to the fact that each layer has a very different purpose and construction and must meet different, individual performance requirements.

Starting from the outside and moving toward the skin, the first layer of protection is the outer shell, followed by the moisture barrier and ending with the garment layer closest to the skin, the thermal liner. Most of the time the thermal liner is recognized as a single component, but occasionally it will be referred to as two separate components. These components would be the thermal batting (or thermal liner) and the face cloth (or inner liner) [25, 50]. All of these components would make up the garment composite which is, as mentioned earlier, used in the construction of the turnout coat and pants. The clothing underneath the garment is also important to consider since it is part of the total package of body protection. A station uniform, or at least a cotton t-shirt, is advised while synthetics such as nylon or polyester should not be considered [50].

### 2.4.1 Outer Shell

The outer shell is the first line of defense against the heat and flame. There are two crucial functions of the outer shell: it must resist ignition from direct flame contact and it must protect the rest of the garment from rips, tears, slashes, abrasion, etc. [50]. A typical outer shell, thus, would consist of a woven fabric constructed of high strength, heat- and flame-resistant fibers. Some outer shells can provide some amount of improved thermal protective performance (TPP) or offer better resistance against water absorption than others. However, first and foremost, the outer shell must be able provide continued protection for the internal layers of the garment throughout the lifetime of the garment. This means it must be able to withstand extreme temperatures and the great deal of wear and tear involved in firefighting while maintaining its protective qualities [50].

### 2.4.2 Moisture Barrier

The moisture barrier is situated between the outer shell and the thermal liner. Its main purpose is to keep out water and other liquids [50]. There are several reasons for doing this. First, a dry system is safer, more dependable, and lighter than a wet system [50]. Steam and scald burns that already occur because of sweat accumulation would become even more of a risk. These burns often come as a surprise to firefighters since they can occur without even having contact with a flame or hot surface and often show no damage to the turnout system [46]. Also, the thermal protective properties of the system can be compromised if water is allowed to penetrate into the critical air spaces of the thermal liner [50]. The thermal conductivity of water is about 21 to 23 (depending on the temperature) times higher than that of air [40, 46]. This higher heat transfer rate (reduced thermal insulation) means the firefighter would be more susceptible to sustaining burn injuries [46]. Yet another consideration is the added weight and constriction of the garment. The added weight of the water would increase energy costs; plus, wet garments have been reported to allow reduced freedom of movement [51, 52]. A final point is that water is not the only liquid of concern. Moisture barriers are also designed to keep out other liquids including bodily fluids that may be carrying blood-borne viruses [39, 53]. This is important in keeping firefighters safe from diseases when handling victims. In addition to preventing water from getting into the system, the moisture barrier should also allow some amount of moisture vapor to exit the system [25]. In general, moisture barriers are constructed of a product similar to a film of plastic laminated to a fabric (woven or non-woven) substrate [25]. Any time coatings, membranes or other treatments are added to fabrics, such as in this case, diffusion of vapor molecules is involved and there is a major effect on the vapor resistance [27]. The moisture barrier is thus a significant hurdle for evaporative sweat loss and should be highly breathable to reduce the amount of heat and moisture that are trapped inside the system [38, 50].

### 2.4.3 Thermal Liner

The innermost layer of protection in the garment is the thermal liner. The most efficient method of construction for the thermal liner has been found to be the use of multiple layers, each designed for a specific purpose [50]. The thermal batting provides for most of the insulation in the garment. Typically, it is a non-woven fabric constructed from some arrangement of thermal-resistant fibers. Often the batting itself consists of multiple layers. This strategy allows the liner to trap more air, which is not only the single best source of insulation in the garment, it is also nearly weightless and free [50]. Quilted to the thermal batting towards the skin is a light, woven fabric known as the face cloth. Face clothes often use long slippery and flexible yarns that allow for greater comfort and mobility in the turnout gear [50]. Face clothes also, by nature of some of the same properties, tend to wick moisture away from the body thus reducing feelings of discomfort associated with skin wettedness [50].

## 2.5 Modifying Clothing: Performance Evaluation

Turnout gear, because of all its requirements, poses a great risk for heat stress. It is a relatively heavy, multiple layer system that necessarily will be both insulative and water vapor resistant [34]. It is this concern that has led the NFPA to set a requirement on turnout gear that attempts to limit the amount of heat stress imposed by turnout gear [54]. A task force was formed with the goal of developing a test methodology that could distinguish heat stress potential between garments within the range of interest [54]. The test needed to be reproducible, verifiable, and easily understood within the fire industry [54]. Their efforts resulted in the development of a test method based on the guarded sweating hot plate which they found to meet all of their outlined objectives [54].

### 2.5.1 Total Heat Loss Test

Throughout 1989 the NFPA Technical Committee on Protective Clothing and Equipment held a series of meetings to review options to address the issue of heat stress in the upcoming (1991) revision to NFPA 1971 [54]. The result was the development of the total heat loss (THL) test. However, there was apprehension to add a material requirement to address heat stress because of the possible compromise to the garments protective capability [45, 54]. Instead, with the debate as to the practicality of the test becoming part of the standard still ongoing, it was added merely as an appendix; it also made note that only in low to moderately stressful environments would the material differences in turnout garments be meaningful [45, 54, 55]. Researchers continued to investigate the issue during throughout the next decade, but still the test did not become part of the standard when the next revision came out in 1997 [56]. At the end of 1998, however, a report was released claiming the predictive capability of the THL test [41]. In the same year, a similar study found significant physiological differences between a non-breathable garment (THL value of 97 $W/m^2$) and other breathable garments (THL values ranging from 146 to 251 $W/m^2$) [48]. Little more than a year later, the NFPA convened early and released the new 2000 edition of the NFPA 1971 standard [56]. This version included the THL test with a minimum requirement of 130 $W/m^2$ as part of the standard [39]. The 2000 edition remains current as of right now, but will be updated in the upcoming 2006 edition where a new THL requirement of 205 $W/m^2$ is anticipated.

### 2.5.2 Development of the Total Heat Loss Test

The total heat loss test is based on the guarded sweating hot plate. It was developed, as aforementioned, in 1989 through the NFPA Technical Committee on Protective Clothing and Equipment [54]. In the first of the seven meetings in 1989, a heat stress task force was organized from which sprung a sub task force that was created in order to identify what test methods existed that could measure fabric or ensemble properties as they might relate to heat stress in firefighting [54]. They were also charged with providing data from one or more of the test methods identified for relevant fabrics or garments and making a recommendation based on evaporative and conductive measurements [54].

In the second meeting in 1989, after reviewing the literature and the availability of the test apparatuses for testing, one test was identified for thermal insulation measurements (ASTM D1518) and three tests were identified for evaporative transfer measurements (Sweating Guarded Hot Plate, Canadian method CAN2-42-M77, and ASTM E96B or BW) [54]. Manikins were also considered but rejected because of limited availability and cost [54]. The heat stress task force, based on the capability to measure layered ensembles and compatibility with thermal balance theory, guided the sub task force to focus on the guarded hot plate and sweating guarded hot plate [54].

During the third meeting, it was decided that differences in apparatuses could be overcome by calibrating to a standard and that non-isothermal conditions would be used to represent a more realistic situation. The evaporative resistance term was also modified by the addition of the word 'apparent' to reflect that condensation might occur during testing [54]. Discussion of which procedure to use also began at this meeting. Though concluded later, it was eventually decided that the plate would be kept at 35 ºC and the environmental conditions would be 25 ºC and 65% relative humidity in the air stream [54].

In the fourth meeting, tolerances were set at ±10% for inter- as well as intra-laboratory testing [54]. In the fifth meeting it was decided that the total heat loss of the ensemble would be 'reported.' This was considered somewhat of a ideal compromise stemming from the discussion of whether to use resistance values (introduced by

Randolph in 1912) or thermal insulation (clo) and permeability index ($i_m$) (introduced by Woodcock in 1961) [54]. In the sixth meeting calibration issues were settled the standard method was finalized; in the seventh and final meeting inter-laboratory results were compared and the validity of the test was confirmed [54].

### 2.5.3 ASTM F-1868 Standard

The NFPA 1971 standard requires that the hot plate testing be done in accordance with the official American Society for Testing and Materials (ASTM) F-1868 Standard Test Method for Thermal and Evaporative Resistance of Clothing Materials Using a Sweating Hot Plate, originally adopted in 1998 [39, 57]. This standard could be viewed as the final result of the work started by the heat stress task force almost ten years prior and much of the original method remains intact.

For realistic evaluation of a protective garment's heat transfer capabilities, one must be able to evaluate both the thermal (dry) and evaporative resistances of a garment [58]. The ASTM F-1868 standard calls for the use of a guarded sweating hot plate, which can be used (either dry or sweating) for evaluating both thermal and evaporative resistances [57]. NFPA 1971 and ASTM F-1868 lay out most specifications for the testing apparatus and procedure. However, there is some amount of leeway in the standard as to the exact specifications. In order for a garment to pass the NFPA standard, it must be certified by an approved, independent third party. The methods described here reflect the specifics of the hot plate at NCSU which is set up and operated in accordance with testing facilities that regularly perform garment certifications.

### 2.5.4 Measuring Thermal Resistance

To measure the thermal resistance ($R_{ct}$) of a fabric or layered fabric system, a square sample is cut to fit the dimensions of the outer plate (20" by 20") and is then laid flat atop the plate. An inner heater and plate assembly (approximately 10" by 10") is heated to 35 ºC to approximate human skin temperature [58]. The ensemble is layered and oriented as it would be constructed and worn in the garment with the face cloth toward the plate (skin) and the outer shell exposed to the ambient environment [39]. A 30" guard heater surrounds the inner heater to prevent lateral heat flow to or from the main, inner heater [59]. A second bucking heater is located beneath the main heater to eliminate axial heat flow away from test sample. All of the heat generated by the main heater is thereby directed toward the test sample [59]. The entire plate assembly is housed in an environmental test chamber that it set to keep the air at 25 ºC and 65% RH. A fan system also located within the chamber is set to control air flow across the test sample at 1.0 m/s. A computer controlled system measures the amount of electrical power required to keep the plate at a constant temperature in steady state conditions which is proportional to heat loss through the fabric system [58].

### 2.5.5 Measuring Evaporative Resistance

Evaporative resistance ($R_{et}$) is measured in much the same way with a few, key differences. The procedure and controls are basically the same with the main difference being that water is fed to the porous surface of the plate [58]. A fluoropolymer membrane acts as a liquid barrier positioned on top of the plate to prevent water from wetting the fabric while allowing water vapor to evaporate through the fabric system [58]. Taking into account the thermal resistance of the particular fabric system, the new power requirement is related to the amount of water evaporating per unit time and the latent heat of vaporization [58]. Because non-isothermal conditions are used some amount of condensation may occur, so the resistance calculated is termed 'apparent evaporative resistance' ($R_{et}^{A}$ or $AR_{et}$) rather than pure 'evaporative resistance' [54]. The THL value ($W/m^2$) called for by the NFPA 1971 standard can then be calculated from the $R_{ct}$ and $AR_{et}$ values.

### 2.5.6 Calculations

The thermal resistance (resistance to dry heat) is calculated based on measurements of the surface temperature, test chamber air temperature, input power to the main heater and geometry of the test samples according to the following equation:

$R_{ct} = (T_s – T_a)A/H_c$, where

> $R_{ct}$ = resistance to dry heat transfer provided by the fabric system and surface air layer ($K{\cdot}m^2/W$),
>
> $A$ = area of the plate test section ($m^2$),
>
> $T_s$ = surface temperature of the plate (ºC),
>
> $T_a$ = air temperature (ºC), and
>
> $H_c$ = power input (W) [57, 59].

The evaporative resistance is calculated based on measurements of the dry thermal resistance, the input power to the main heater when the porous surface plate is wetted, the surface temperature, the test chamber air temperature, the saturated water vapor pressure at the surface of the porous plate, the water vapor pressure of the test chamber air, and the geometry of the test samples according to the following equation:

$AR_{et} = [(P_s - P_a)A] / [H_T - (T_s - T_a)A/R_{ct}]$, where

$AR_{et}$ = apparent total evaporative resistance of the specimen and surface air layer (kPa·m²/W)

$P_s$ = water vapor pressure at the test plate surface (kPa),

$P_a$ = water vapor pressure in the air flowing over the specimen (kPa),

A = area of the plate test section (m²),

$H_T$ = power input (W),

$T_s$ = temperature at the test plate surface (ºC),

$T_a$ = temperature in the air flowing over the specimen (ºC), and

$R_{ct}$ = total thermal resistance of the specimen and surface air layer (K·m²/W) [57, 59].

In order to determine the THL value of a fabric, one must first determine the intrinsic thermal resistance of the sample alone ($R_{cf}$) and the intrinsic evaporative resistance of the sample alone ($AR_{ef}$). The $R_{cf}$ is determined by subtracting the average bare plate resistance ($R_{cbp}$) from the average total thermal resistance ($R_{ct}$) of the samples tested, and the $AR_{ef}$ is similarly determined by subtracting the average bare plate evaporative resistance ($R_{ebp}$) from the average apparent total evaporative resistance ($AR_{et}$) of the samples tested [57]. Once these values have been obtained, the THL valued can then be calculated according to the following equation:

$$Q_t = [(T_s - T_a)/(R_{cf} + K_c)] + [(P_s - P_a)/(AR_{ef} + K_e]$$

$$= [10.0^{o}C/(R_{cf} + 0.04)] + [3.57kPa/(AR_{ef} + 0.0035)], \text{ where}$$

$Q_t$ = total heat loss ($W/m^2$)

$R_{cf}$ = average intrinsic thermal resistance of the laboratory sample ($K \cdot m^2/W$),

$R_{ef}$ = average apparent intrinsic evaporative resistance of the laboratory sample ($kPa \cdot m^2/W$),

$T_s$ = temperature at the test plate surface (ºC),

$T_a$ = temperature in the air flowing over the specimen (ºC),

$P_s$ = water vapor pressure at the test plate surface (kPa),

$P_a$ = water vapor pressure in the air flowing over the specimen (kPa),

$K_c$ = dry apparatus constant for nominal effective air velocity, and

$K_e$ = wet apparatus constant for nominal effective air velocity [36, 54, 57].

The nature of the test design also allows the thermal and apparent evaporative resistances to be easily converted into thermal insulation (clo) and permeability index ($i_m$) according to the following equations:

$clo = R_{ct} * 6.45$, where clo = unit of thermal insulation and

$R_{ct}$ = thermal resistance ($K \cdot m^2/W$);

$i_m = (R_{ct}/AR_{et}) * 0.061$, where $i_m$ = permeability index,

$R_{ct}$ = thermal resistance ($K \cdot m^2/W$), and

$AR_{et}$ = apparent evaporative resistance ($kPa \cdot m^2/W$)

### 2.5.7 Balancing Total Heat Loss with Thermal Protective Performance

THL, though most relevant to heat stress, is not the only pertinent requirement in the NFPA 1971 standard. It should be remembered that limiting heat stress is only one aspect of firefighter safety. The need for the stress-imposing gear is to allow firefighters to do their jobs, and burn injuries and fatalities will always be of paramount concern [1, 46]. The primary test within NFPA 1971 standard regulating thermal protection for the wearer (beyond the material requirements to withstand the extreme temperatures) is the thermal protective performance (TPP) test. The test uses a bank of quartz radiant tubes and two Meeker burners to provide an approximately equal balance of convective and radiative heat exposure to the test specimens [60]. The thermal exposure is designed to represent a moderate flash fire condition and can be used to predict the potential for burn injuries in a similar situation [25]. The minimum requirement to pass the standard is a TPP rating of 35 which equates to 17.5 seconds until second degree burns would be produced in a flashover condition [25].

Total heat loss and thermal protective performance are often thought of as trade-offs for one another because of the seemingly inherent contradiction. Figure 2.2 shows the general negative correlation between THL and TPP (plotted from data publicly available from Fire Safe Associates) [61].

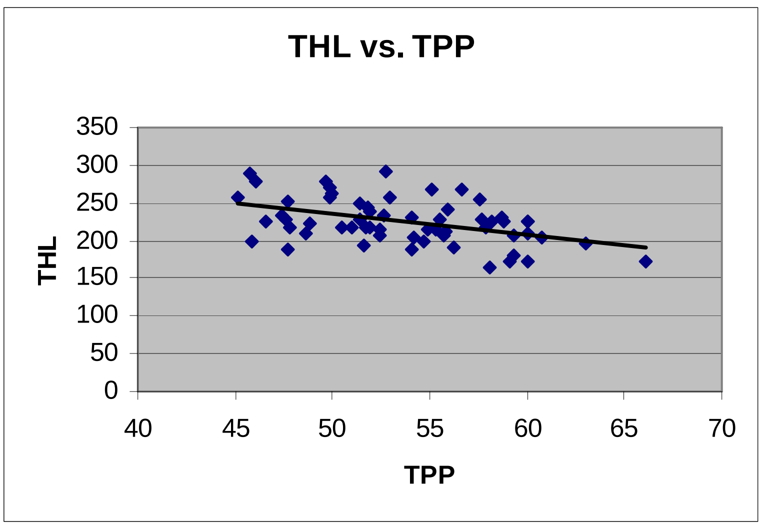



**Figure 2.2: THL vs. TPP for Garment Composites from 4 Various Outer Shells, 3 Various Moisture Barriers and 5 Various Thermal Liners**

Although the correlation is fairly weak, it is a very typical trend in firefighter garments. Figure 2.3 shows another example of the negative correlation that has been found to exist (modified from a graph from an article by Ron Bove in Technology Today titled "Total Heat Loss") [62].

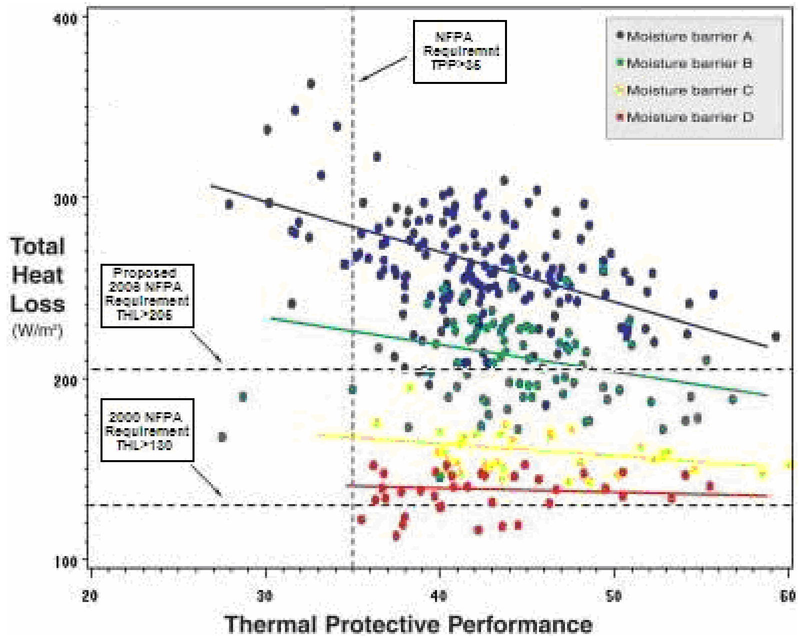



**Figure 2.3: Typical Negative Correlation between THL and TPP for Several Garments (Color Separated by Moisture Barrier)**

In Figure 2.3, the effect of the moisture barrier is obvious per the separation and varying slopes of the regression lines. This could be one explanation for why there is a relatively weak correlation in Figure 2.2 where three fundamentally different moisture barriers were included in the dataset. Moisture barriers affect heat loss mostly through their limited evaporative heat transfer and thus can make a difference of more than 100 points in the THL rating while having no appreciable impact on TPP [50]. By the same logic, THL and TPP are not absolute trade-offs for one another, but can be optimized by strategically selecting each component of the garment.

In Figure 2.2, it appears that many of the ensemble configurations involving moisture barrier B, as well as even a few involving moisture barrier A, do not meet the proposed 2006 NFPA requirement for THL of 205 W/m². The lower two moisture barriers (C and D) appear to have THL values ranging from about 115 to 200 W/m², a range in which none of the configurations would meet the new requirement. It is likely that these latter two moisture barriers could represent outdated technologies as far as firefighting moisture barriers are concerned. However, there is no indication of the barrier properties or the outer shell and thermal liners that were used to generate this data so as to substantiate this idea. An apparent trend in Figure 2.3 is the increasing slopes of the regression line as the THL increases. The most likely explanation for this phenomenon is that as THL becomes less dependent on the moisture barrier, it becomes more dependent on the insulative properties of the thermal liner. It is well known that permeable (breathable) moisture barriers provide much higher THLs than impermeable barriers when laid up with the same outer shell and thermal liner [55]. McCullough reports evaporative resistances measured on the sweating hot plate to have strong correlations (up to 91% Spearman correlation) with several water vapor transmission tests [47]. Therefore, selecting a permeable membrane to allow maximum evaporative heat transfer should allow the garment to be optimized by careful selection of the thermal liner, which has the greatest impact on TPP as well as a considerable impact on THL [50]. The ability to increase total heat loss without necessarily compromising thermal protection is a very important and realizable endeavor.

### 2.6 Limitations of the Sweating Hot Plate Test

Although the sweating hot plate is a very useful tool for assessing heat stress potential, it is not without limitations or troubles. Proper operation often proves to be very tedious and time-consuming. With so many variables to be controlled, reaching steady state is often quite difficult. During wet testing, since non-isothermal conditions are used, any tests that run over 4 hours must be aborted and samples reconditioned before attempting to test the same specimen because of the effects of condensation [58]. Also, getting fabrics to stay flat on the plate can be quite an issue. All firefighter garments contain a moisture barrier. If this barrier is constructed of a hydrophilic coating or laminate as many are, its vapor permeability will increase as it becomes hydrated [58]. If these barriers can absorb moisture from the plate, swell, ripple and lift off the plate. When this happens air gets trapped within the specimen causing abnormally high evaporative resistances to be measured [58].

Similar problems can arise in connection with the air flow stream. Often, especially with thicker samples, relatively high fan speeds are needed in order to achieve the nominal 1 m/s wind speed above the fabric sample. These higher fan speeds have, at times, somehow blown air under the fabric causing it to lift off the plate and create the same high resistance problem for either dry or evaporative testing. Also, because the air flow is horizontal, it reaches the leading edge of the hot plate first gaining heat and/or humidity as it crosses the plate making for a non-uniform ambient environment [58]. Temperature probes have also shown there to be differences across the plate itself under the standard 1 m/s wind condition with a firefighter garment sample laid atop of it. Apparatuses with vertical air flow do not have these problems, but very few laboratories have the capability to do this [58].

### 2.6.1 Fabric versus Clothing

One major limitation of the sweating hot plate is that it can only provide intrinsic values for fabrics, not clothing. The results, therefore, cannot accurately describe the entire garment without consideration of the amount of body surface area covered by different fabrics, distribution of the fabric and air layers on the body, the fit, and the increased surface area for heat loss [58]. For firefighter garments, there is also the consideration of trim, pockets, flaps and other hardware or accessories that make up part of the clothing system. Therefore, there is the potential for much disconnect between the material values measured by the sweating hot plate and how they would perform in actual wear conditions.

### 2.6.2 Heat Transfer with the Hot Plate

Another potentially significant difference between hot plate testing and realistic wear conditions of the garment is the different ways in which heat is transferred and thus measured with the hot plate versus real life. The hot plate composite consists of the three individual layers of the firefighter garment. These layers are set atop one another flat and level. Air layers are minimal and heat loss is considered to be uniform. It is not in fact, but differences are considered to be minor. One of the causes of these differences in our lab is the aforementioned fan which blows across the surface of the composite from behind the plate causing it to be cooler towards the back and warmer towards the front. However, since the active sensor is in the center of the plate, it may be that the difference cancels itself out. Although, it should not be ignored that nearly all of the air is moving across the surface of the fabric in a direction nearly parallel to the surface. This is hardly representative of actual wind conditions on a human body [58]. That may be a minor point, but the avenues of heat loss in general may not be so minor.

There are many aspects of the sweating hot plate test that cause it to be much less representative of actual heat transfer than that which may be possible with other research tools. First, layers are flat atop one another which may exaggerate dry microclimate conduction. This also means that there is a lack of fully developed boundary air layers [40]. This not only reduces the total insulation but also restricts evaporative mass transfer by convection when interlayer air movement is possible [40]. In wet testing, only water vapor can pass through the membrane so liquid development at the surface (skin) is minimal and thus wet conduction may be underestimated. Minimal liquid at skin also may not allow for proper consideration of transport through capillary action or evaporation at other locations [40]. Another big limitation of the sweating hot plate is that it does not consider convection that is possible from ventilation or body motion [63]. In fact, the convection must almost necessarily be only from the outer shell where all heat must escape through the material. In reality there are many avenues in which heat may escape around the material.

The hot plate considers the main composite material only. It does not consider aspects of garment design, such as pockets, zippers, trim, etc. It also does not consider other parts of the body where other articles of clothing are worn. It does not consider one's head, hands, or feet. It does not consider how the SCBA pulls the garment against the body. It does not consider what one may be wearing under his suit, how these garments might fit up against one another, or be compressed by the body or garment on one another. These are significant considerations to keep in mind; the hot plate is a valuable tool, but it does not represent how realistic wearing conditions may affect heat stress.

### 2.7 The Sweating Manikin as a Supplemental Tool

Still, the hot plate remains the standard test for heat stress, and the NFPA is actively raising performance requirements on its merit. There are tests, though, which exist and are becoming more popular in recent years. One of the most promising tests is the use of a sweating thermal manikin. The sweating manikin is basically a hot plate in human form [58]. This allows for it to take advantage of the principles of the hot plate method without so many of its issues of capability. Since the sweating manikin has the form of a human being, garments fit on the manikin as they would with an actual person. The human form of the manikin is important for many reasons. Since the full garment can be applied as it would be worn in realistic situations, the mechanisms of heat transfer should be closer to those of a human being than the sweating hot plate. The garment is able to be evaluated where the actual construction, fit, air layers, and other various elements of the design can be considered [58]. The manikin used in this research is limited in that it is static and so cannot address the pumping issue of body motion, but still can consider ventilation which can be significant [63].

## 2.8 Physiological Wear Trials

Even though other sophisticated measurement technologies, such as thermal manikins exist, in the recent past and still today much focus throughout the industry has been on assessing the value of the hot plate. If the hot plate is deemed adequate to provide information to predict heat stress and set performance requirements, it is a rather cheaper and more widely available tool than most viable alternatives. Since heat stress has continued to be a considerable concern in the industry, it is not surprising that many have seemingly lobbied for performance requirements to be raised. In order to make meaningful decisions on raising performance requirements, however, research was needed to assess how the information provided by the hot plate could be translated into some physiological response indicating a credible risk of heat stress. The primary means of doing so was through physiological testing in which material properties could be measured and then compared with physiological responses such as skin temperature, core temperature, heart rate, etc. that would be measured in a controlled laboratory experiment using human subjects. Two of the more prominent reports which have been presented to and reviewed by the NFPA for making the assessments such described were the International Firefighter Protective Clothing Breathability Research Project and the Field Evaluation of Protective Clothing Effects on Fire Fighter Physiology: Predictive Capability of the Total Heat Loss Test.

### 2.8.1 International Firefighter Protective Clothing Breathability Research Project

The International Firefighter Protective Clothing Breathability Research Project was conducted at North Carolina State University in 1998 under the leadership of Dr. Roger Barker of NCSU and Dr. Loren Myrhe of Alamo Physiological Research Institute. The study was divided into two parts: a Mild Environment Protocol and a Warm Environment Protocol. Although the protocols were very different, other aspects of the study were designed in a parallel fashion. For both protocols physiological data was recorded and consisted of core temperature, skin temperatures (chest, arm, back, and thigh), and heart rate. Microclimate humidity was measured inside the turnout near the subjects back. Also, subjects and their clothing were weighed pre- and post- testing to assess moisture loss in subject (evaporation) and moisture gain in clothing (absorption). In addition to the objective data gathered, subjects were also asked to rate the clothing (or their response to the clothing) subjectively for overall wear comfort, heat sensation, skin moistness, heaviness, flexibility, fatigue, fit, sense of protection, and overall like or dislike [48]. Other issues of preparation, data collection, and general execution were also very similar for the two protocols. Basically the only differences in the protocols were those which were by design, including the test conditions, the configuration of clothing worn, and the exercise routine.

#### 2.8.1.1 Mild Environment Protocol

Part 1 of the study, the Mild Environment Protocol, was designed to represent a mild climate with light to moderate work activity [48]. Subjects wore turnout coats and pants over a station uniform and underwear with socks and walking shoes. The turnout garments consisted of six NFPA compliant systems with total heat loss values (hot plate) ranging from 97 to 251 W/m$^2$ [48]. The garments used were the same as those tested on the manikin and further details about each garment can be found in Chapter 3 of this report. The environmental conditions were set at 21ºC, 65% RH to represent a 'mild' climate [48]. Table 2.1 outlines the experimental protocol that was followed [48].

**Table 2.1: Mild Environment Protocol for Breathability Research Project**

| Test Period | Time (min.) | Cumulative Time (min.) | Activity | Physiological Measurements* | Subjective Ratings |
|---|---|---|---|---|---|
| Pretest Baseline | | | Prior to donning turnout | Initial $T_s$, $T_{re}$, HR | |
| 1 | 15 | 1 - 15 | Rest | $T_s$, $T_{re}$, % RH, HR @ 5 & 15 min. | End of period |
| 2 | 20 | 15 - 35 | Walk 2% grade treadmill @ 2.5 mph | $T_s$, $T_{re}$, % RH, HR @ 5 min. intervals | End of period |
| 3 | 30 | 35 - 65 | Rest | $T_s$, $T_{re}$, % RH, HR @ 5 & 25 min. | End of period |
| 4 | 20 | 65 - 85 | Walk 2% grade treadmill @ 2.5 mph | $T_s$, $T_{re}$, % RH, HR @ 5 min. intervals | End of period |
| 5 | 30 | 85 - 115 | Rest & cool down | $T_s$, $T_{re}$, % RH, HR @ 5 min. intervals | End of period |

*$T_s$ = Skin temperature of chest, back, arm and thigh
% RH = percent relative humidity in the clothing microclimate
$T_{re}$ = Rectal temperature
HR = Heart rate

Once the all of the sessions were completed, all of the data was compiled and analyzed. The following findings were reported:

- Regardless of turnout worn, light work in a moderate environment does not result in a significant increase in core temperature; the max rise (<0.6C) did not approach physiological heat stress limits for any of the garments worn;
- No significant differences in either core temperature or heart rates were observed that could be correlated with differences in turnout breathability;
- There are small but significant differences in skin temperature of different turnout garments (Garment 4 generates the highest skin temperature);
- Major changes in humidity are highly associated with changes in physical activities, far more so than differences in the garment material components; still microclimate humidity buildup increases as the composite sweating hot plate total heat loss value decreases;
- Analysis of subjective data indicates that firefighters can decisively perceive and differentiate among composites on the basis of comfort sensations only for Garment 4 (non-breathable); the most significant differences were reported for feelings of warmth and skin wetness;

- The significantly greater weight gain of Garment 4 corresponds with the subjective evaluation in which Garment 4 was rated as generating the greatest feeling of skin wetness [48].

Based on these findings the researches concluded that for these low work loads, in a mild environment, physiological heat stress limits were not approached, regardless of the "breathability" of the turnout composite. They also noted that there was no indication that core temperature or heart rates were significantly affected by differences in turnout breathability for these conditions. They did, however, recognize that differences in turnout breathability could be associated with perceived levels of comfort (higher THL values related to lower skin temp and less moisture buildup in microclimate). These differences, however, were only decisively perceived for Garment 4. Particularly, Garment 4 was noted to produce greater feelings of warmth and skin wetness in the wearer seemingly due to its non-breathability [48]. On the whole, the researchers' general conclusion seemed to be that in these mild conditions differences between garments were minor with the only real difference being a perception of moderate discomfort imposed by wearing the non-breathable garment.

#### 2.8.1.2 Warm Environment Protocol

Part 2 of the study, the Warm Environment Protocol, was designed to represent a warm climate with moderate work activity [48]. Subjects wore the same turnout coats and pants as in the Mild Environment Protocol, also worn over a station uniform, but with all of the additional gear as would be worn during structural firefighting. As in the Mild Environment Protocol, the subjects wore walking shoes rather than boots. Otherwise they were dressed exactly as if they would be entering a fire scene except that their SCBA regulator was not attached to the facepiece so that they could breathe the ambient air [48]. The environmental conditions were set at 39ºC, 35% RH to represent a 'warm' climate [48]. Table 2.2 outlines the experimental protocol that was followed [48].

**Table 2.2: Warm Environment Protocol for Breathability Research Project**

| Test Period | Time (min.) | Cumulative Time (min.) | Activity | Physiological Measurements* | Subjective Ratings |
|---|---|---|---|---|---|
| Pretest Baseline 1 | | | Prior to donning turnout | Initial $T_s$, $T_{re}$, HR | |
| Pretest Baseline 2 | | | Prior to donning SCBA | $T_s$, $T_{re}$, HR | |
| 1 | 15 | 1 - 15 | Walk 2% grade treadmill @ 2.5 mph | $T_s$, $T_{re}$, HR @ 5 min. intervals %RH every min. | |
| 2 | 2 | 15 - 17 | Rest | $T_s$, $T_{re}$, HR @ end of period %RH every min. | While Resting |
| 3 | 15 | 17 - 32 | Walk 2% grade treadmill @ 2.5 mph | $T_s$, $T_{re}$, HR @ 5 min. intervals %RH every min. | |
| 4 | 2 | 32 - 34 | Rest | $T_s$, $T_{re}$, HR @ end of period %RH every min. | While Resting |
| 4 + n** | 15 | 17 + 17*n – 19 +17*n | Walk 2% grade treadmill @ 2.5 mph | Ts, Tre, HR @ 5 min. intervals %RH every min. | At End of Final Work Cycle |
| 5 + n | 2 | 19 + 17*n – 21 + 17*n | Rest | Ts, Tre, HR @ end of period %RH every min. | While Resting |

*$T_s$ = Skin temperature of chest, back, arm and thigh
% RH = percent relative humidity in the clothing microclimate
**Work/Rest cycles continued until either subject's $T_{re}$ reached 39ºC or he was unwilling or unable to continue for any reason
$T_{re}$ = Rectal temperature
HR = Heart rate

Once the all of the sessions were completed, all of the data was compiled and analyzed. The following findings were reported:

- The minor differences in core temperature and heart rate between garments were not statistically significant;
- Differences in mean skin temperatures were not statistically significant for any of the garments during the first work cycle but did become significant at later times (limited to 0.3 to 0.9°C) for Garment 4 when compared with the others; there was no correlation between sweating hot plate values and mean skin temperature for any garment;
- Work tolerance time (predominately subjective) was significantly less for Garment 4 than all other garments; the actual difference was about 6-7 minutes (13% less than the breathable-garment average) and correlated well with mean skin temperature;
- When considering each garments sweating hot plate value, no statistical differences were found for any of the physiological indices of heat stress during the first 30 minutes of work. Thereafter, only mean skin temperature was significantly different and only for Garment 4; no other garments were significantly different from one another, regardless of sweating hot plate values;
- Several of the subjective responses indicated significant comfort disadvantages associated with Garment 4, particularly that it was hotter and caused greater sensations of skin wetness;

- Garment 4 produced the highest sweat accumulation and lowest sweat evaporation, which correlate with subjective perceptions of skin wettedness. However, regardless of the breathability, the total amount of sweat evaporated averaged less than 10% of the total sweat produced. Though statistical significances exist between garments, this small volume would be insignificant with respect to protecting from cumulative heat stress for any garment [48].

Based on these findings the researches concluded that the guarded sweating hot plate test could be used to assess a minimum amount of total heat loss which would predict diminished garment performance in some categories of heat stress and perceived discomfort. No physiological indices or comfort perceptions indicated that any of the breathable garments (THL values ranging from 146 to 251 W/m$^2$) could be distinguished from one another. The only garment with a measurable impact in any category was Garment 4, a non-breathable garment with a THL value of 97 W/m$^2$. While none of the garments indicated a significant difference in core temperature, Garment 4 produced higher skin temperatures and was perceived as hotter with greater sensations of skin wetness. Also, firefighters, who all continued to exercise until they complained that they could not go on, stopped exercise an average 6.8 minutes (significantly lower) earlier with Garment 4 compared with all other garments [48]. All indications, therefore, pointed to the non-breathable Garment 4 being the only garment that would impose any additional stress to its wearer beyond that imposed by any typical firefighting garment.

### 2.8.2 Field Evaluation of Protective Clothing Effects of Fire Fighter Physiology: Predictive Capability of Total Heat Loss Test

The Field Evaluation of Protective Clothing Effects of Fire Fighter Physiology was conducted in 1998 by the International Association of Fire Fighters (IAFF) under the technical direction of Jeffrey O. Stull. The study was divided into two parts: an Extrication Simulation Protocol and a Ladder Company Simulation Protocol. Although some aspects of the protocols were different, most facets of the study were very similar. For both protocols physiological data was recorded and consisted of core temperature, skin temperatures (arm and thigh), and heart rate. Also, subjects and their clothing were weighed pre- and post- testing to assess moisture loss in subject (evaporation) and moisture gain in clothing (absorption). In addition to the objective data gathered, subjects were also asked to rate the clothing (or their response to the clothing) subjectively for overall wear comfort, heat sensation, skin moistness, heaviness, flexibility, fatigue, fit, sense of mobility, and ease of donning/doffing [41]. Other issues of preparation, data collection, and general execution were also very similar for the two protocols. Basically, the only differences in the protocols were those which were by design, including the test conditions, the configuration of clothing worn, and the exercise routine.

#### 2.8.2.1 Extrication Simulation Protocol

The first part of the study, the Extrication Simulation protocol, was designed to simulate extrication activity of firefighters in removing a victim from an automobile wreck where heavy tools are used. The environment for this protocol could be considered mild with moderate work [41]. Subjects wore turnout coats and pants over a station uniform, underwear, and socks. Seven different turnout systems were evaluated. Garments 1 - 4 consisted of NFPA compliant systems representing a total heat loss (hot plate) range of 96.5 to 251.5 $W/m^2$. Garments 5 and 6 represented lightweight, low THL systems (103.2 and 111.6 $W/m^2$, respectively); Garment 7 was a lightweight, very high THL system (439.2 $W/m^2$) that contained no moisture barrier or thermal liner. None of the Garments 5 - 7 were NFPA compliant, but were included to provide a greater range of material and garment characteristics. Garments 4, 6, and 7 used a filament facecloth as the innermost layer to provide high lubricity compared to the other garments. In addition to the turnouts, station uniforms, and undergarments, the firefighters also wore all the typical gear (except SCBA) required for structural firefighting including leather boots, helmet, gloves and a protective hood. No SCBA was used for this protocol and the hood was worn in the 'down' position while the neck closure and collar remained open [41]. Testing was carried out in an indoor facility where environmental conditions averaged 20.6ºC, 60.8% RH similar to the conditions of the Mild Environment Protocol of the International Firefighter Protective Clothing Breathability Research Project [41]. Table 2.3 outlines the experimental protocol that was followed [41].

**Table 2.3: Extrication Simulation Protocol for IAFF Field Evaluation**

| Test Period | Time (min.) | Cumulative Time (min.) | Activity | Physiological Measurements* | Subjective Ratings*** |
|---|---|---|---|---|---|
| Pretest Baseline | -5 | -5 - 0 | Rest, don gloves | $T_s$, $T_{re}$, HR monitored continuously** | Prior to donning gloves |
| 1 | 10 | 1 - 10 | Walk @ 4 mph | $T_s$, $T_{re}$, HR monitored continuously | |
| 2 | 5 | 10 - 15 | Carry tools | $T_s$, $T_{re}$, HR monitored continuously | |
| 3 | 5 | 15 - 20 | Simulate use of tools (pick up tools and perform specified number of actions or cutting) | $T_s$, $T_{re}$, HR monitored continuously | |
| 4 | 5 | 20 - 25 | Carry tools | $T_s$, $T_{re}$, HR monitored continuously | |
| 5 | 5 | 25 - 30 | Walk @ 4 mph | $T_s$, $T_{re}$, HR monitored continuously | |
| 6 | 30 | 30 - 60 | Rest, protective gloves and helmet off | $T_s$, $T_{re}$, HR monitored continuously | 14 - 15 min. prior to end of period |

*$T_s$ = Skin temperature of chest, back, arm and thigh
$T_{re}$ = Rectal temperature
HR = Heart rate
** Every 9 seconds
***Subjective data related to ergonomics was only taken after activity

Once the all of the sessions were completed, all of the data was compiled and analyzed. Many of the findings for the Extrication Simulation were also relevant to the Ladder Company Simulation.

Findings applicable to both simulations will be reported in the next section; the following findings specific to the Extrication Simulation were reported:

- Differences in mean core temperature rise could be seen at the end of activity period (0.2ºC) with significant differences manifesting at the end of the rest period (0.57 ºC spread);
- Three groupings of ending core temperature rise were observed corresponding to the low total heat loss systems (highest rise), systems with THL values in the range of 141.6 to 251.5 $W/m^2$ (intermediate), and the system with no thermal liner or moisture barrier, Garment 7 (lowest rise). Only Garment 7, however, showed to be significantly different based on the p-value criterion of 0.05;
- Ending skin temperature rises exhibited larger ranges for the Extrication Simulation than for the Ladder Company Simulation;
- In the Ladder Company Simulation, garment weight generally provided the best explanation for subjective responses. For the Extrication Simulation, however, other independent variables provided better explanations of subjective responses for heat sensation (THL), flexibility (evaporative resistance), and fatigue (TPP) [41].

Conclusions reported by the researchers were presented based on findings from both exercise protocols. These conclusions, therefore, will be reported in the next section, following a description of the particulars of the Ladder Company Simulation.

### 2.8.2.2 Ladder Company Simulation Protocol

The second part of the study, the Ladder Company Simulation protocol, was designed to simulate activities of a ladder company responding to a structural fire. The environment for this protocol could be considered mild with hard work [41]. Subjects wore turnout coats and pants over a station uniform, underwear, and socks. The turnout systems evaluated were the same seven used in the Extrication Simulation. The additional gear was also worn in the same configuration except that an SCBA was used and the hood was worn in the 'up' position [41]. Testing was carried out in an indoor facility where environmental conditions averaged 20.4ºC, 64.5% RH relatively similar to the conditions of the Extrication Simulation and the Mild Environment Protocol of the International Firefighter Protective Clothing Breathability Research Project [41]. Table 2.4 outlines the experimental protocol that was followed [41].

**Table 2.4: Ladder Company Simulation Protocol for IAFF Field Evaluation**

| Test Period | Time (min.) | Cumulative Time (min.) | Activity | Physiological Measurements* | Subjective Ratings*** |
|---|---|---|---|---|---|
| Pretest Baseline | -5 | -5 - 0 | Rest, don gloves | $T_s$, $T_{re}$, HR monitored continuously** | Prior to donning gloves |
| 1 | 5 | 1 - 5 | Walk @ 3 mph; carry ladder | $T_s$, $T_{re}$, HR monitored continuously | |
| 2 | 1 | 5 - 6 | Climb up and down ladder (3x) | $T_s$, $T_{re}$, HR monitored continuously | |
| 3 | 3 | 6 - 9 | Hammer sledge (5 ft/min.) | $T_s$, $T_{re}$, HR monitored continuously | |

**Table 2.4 (Continued)**

| | | | | | |
|---|---|---|---|---|---|
| 4 | 1 | 9 - 10 | Climb up and down ladder (3x) | $T_s$, $T_{re}$, HR monitored continuously | |
| 5 | 5 | 10 - 15 | Walk @ 3 mph; carry ladder | $T_s$, $T_{re}$, HR monitored continuously | |
| 6 | 15 | 15 - 30 | Rest; gloves, helmet, and SCBA facepiece off, hood down (SCBA air bottle change) | $T_s$, $T_{re}$, HR monitored continuously | |
| 7 | 5 | 30 - 35 | Walk @ 3 mph; carry ladder | $T_s$, $T_{re}$, HR monitored continuously | |
| 8 | 1 | 35 - 36 | 20 simulated ceiling pulls | $T_s$, $T_{re}$, HR monitored continuously | |
| 9 | 3 | 36 - 39 | Simulated search (crawl 75 ft/min.) | $T_s$, $T_{re}$, HR monitored continuously | |
| 10 | 1 | 39 - 40 | 20 simulated ceiling pulls | $T_s$, $T_{re}$, HR monitored continuously | |
| 11 | 5 | 40 - 45 | Walk @ 3 mph; carry ladder | $T_s$, $T_{re}$, HR monitored continuously | |
| 12 | 15 | 45 - 60 | Rest; gloves, helmet, and SCBA facepiece off, hood down | $T_s$, $T_{re}$, HR monitored continuously | 5 min. prior to end of period |

*$T_s$ = Skin temperature of chest, back, arm and thigh
$T_{re}$ = Rectal temperature
HR = Heart rate
** Every 9 seconds
***Subjective data related to ergonomics was only taken after activity

Once the all of the sessions were completed, all of the data was compiled and analyzed. The following findings specific to the Ladder Company Simulation were reported:

- Overall activities were more difficult and all subjects showed higher ending core temperatures; the spread in ending core temperature, however, was less between the best- and worst- performing garments;
- Core temperature differences were more apparent during rest periods; garments did, however, show the same rank ordering for core temperature throughout exercise, once established during the rest period between activity;
- Distinctions in core temperature were clearer for higher total heat loss systems, while those with lower total heat loss values were not easily distinguishable from one another;
- Significant differences in core temperature were much more prevalent than in the Extrication Simulation indicating that core temperature rise could be used to discriminate between ensembles;
- Ending skin temperature rises did not exhibit as large of ranges for the Ladder Company Simulation as for the Extrication Simulation;
- Subjective responses were best explained by garment weight, except for moisture sensation which was better explained by thermal liner lubricity [64].

Some findings were applicable to both the Extrication Simulation and the Ladder Company Simulation. The following findings represent those which were generic to either exercise simulation:

- As expected, skin temperatures changed more rapidly than core temperatures; comparing skin and core temperatures, a more rapid rate of increase was found at the start of activity for skin temperature and earlier declines were noticed, in most cases, during rest for skin temperature;
- Skin temperature plots showed that skin temperatures would begin to recover during rest periods; this was particularly evident for higher total heat loss systems and for the Ladder Company Simulation;
- Heart rate indicated that the activity was sufficient to stress the firefighters during work periods and matched well with activity level but was not a good predictor between garments because inter-individual differences overwhelmed any other measurable variable;
- Nude weight loss averages for particular garments related well to total heat loss values in a rank order comparison; they also indicated that the Ladder Company Simulation was more stressful than the Extrication Simulation;
- Ensemble weight gains were not reported to provide any information that would help distinguish garments in terms of being greater heat stressors;
- Greater differentiation in subjective ratings were observed at the second rating period after subjects experienced the stress of the garment and not just the feel;

- A statistical investigation into the relationship between material system characteristics and physiological responses revealed total heat loss or evaporative resistance in some cases to be the best predictors of physiological responses;
- A strong correlation was found for end core temperature rise and the inverse of total heat loss (1/THL); this indicates an inverse hyperbolic relationship between total heat loss and rise in core temperature [64].

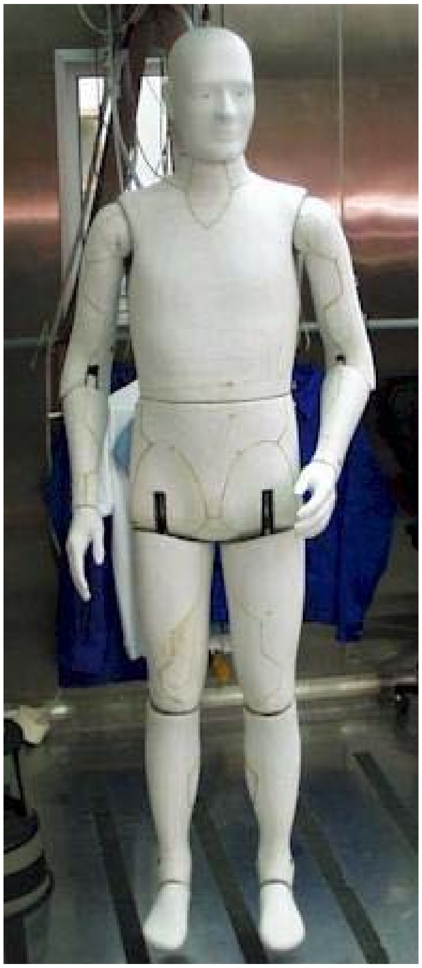
Based on these findings, the researchers concluded that total heat loss values measured by the sweating hot plate could predict physiological responses in representative fire ground operational scenarios better than any other property. Subjective responses were found to be most closely related to weight indicating that studies which rely heavily on subjective responses are likely to be biased by garment weight and not reflect a garment's true physiological impact on its wearer. Heart rate was determined not to be a useful measure of physiological response since it varied more with the individual than anything else [64].

An inverse hyperbolic relationship was indicated by a correlation between 1/THL and rise in core temperature. This hyperbolic model was used to establish baselines; at one extreme, a total heat loss baseline was determined below which physiological benefits would be greater than would be predicted by a linear relationship and at the other extreme, a total heat loss baseline was determined above which physiological benefits would be less than would be predicted by a linear relationship. An underlying assumption in determining these values was that a reasonable breakpoint for assessment would be where the hyperbolic benefits and linear benefits were equal. Based on these values, a minimum detectable change in THL was established in the range of 60 to 70 $W/m^2$ for the conditions of this study. A performance requirement of 170 $W/m^2$ was recommended to the NFPA, which was determined by adding this minimum detectable change to a value (110 $W/m^2$ in this case) typically associated with non-breathable garments [64, 65].

# Chapter 3: Experimental

## 3.1 Manikin Testing

Manikin testing was conducted using the NCSU Sweating Manikin housed in a state-of-the-art climate controlled chamber (maintained by Environmental Specialties, Inc.) located in the Center for Research on Textile Protection and Comfort (T-PACC) laboratory at NCSU. The manikin was built at NCSU and modeled after the sweating thermal manikin Coppelius at the Technical Research Centre of Finland (VTT) in Tampere, Findland. The sweating manikin Coppelius was developed in the 1980's within a Scandinavian cooperation project that based their design on the Swedish dry thermal manikin Tore, with an added sweating capability [66]. Figures 3.1 and 3.2 show the sweating manikin from the front (4) and back with some of its inner components exposed (5).



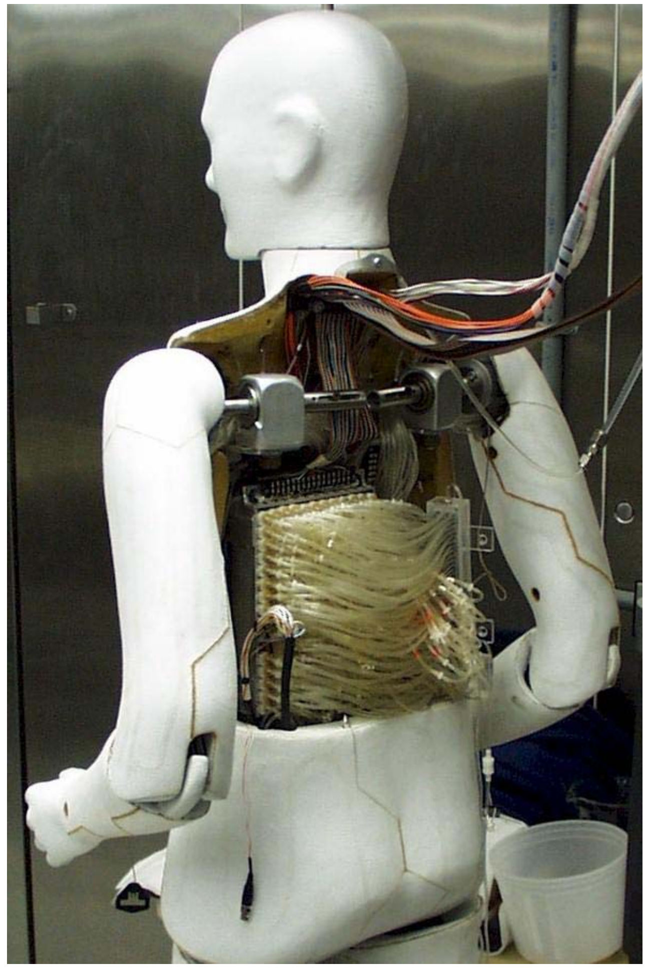
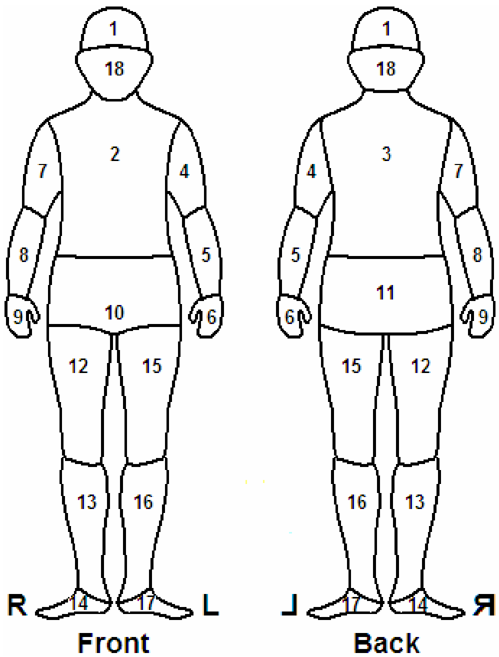


**Figure 3.1: Sweating Manikin (Frontal View)**

**Figure 3.2: Rear View of Manikin's Inner Components**

The NCSU Sweating Manikin consists of 18 separately controlled body sections. Figure 3.3 shows the different sections of the manikin.

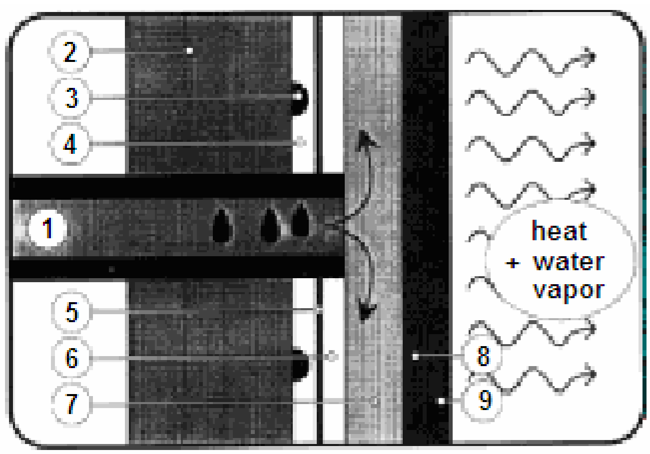



1 – Upper Head
2 – Chest
3 – Back
4 – Left Upper Arm
5 – Left Lower Arm
6 – Left Hand
7 – Right Upper Arm
8 – Right Lower Arm
9 – Right Hand
10 – Standing
11 – Lower Torso
12 – Right Thigh
13 – Right Leg
14 – Right Foot
15 – Left Thigh
16 – Left Leg
17 – Left Foot
18 – Lower Head

**Figure 3.3: Front and Back Views of the Sweating Manikin showing Labeled Sections**

The temperature of each section is controlled by a feedback system where the user sets the desired temperature at a computer interface which then communicates with the sweating manikins control cabinet and the manikin itself. Each section is wired with an RTD sensor that sends an analogue signal to the control cabinet. Data acquisition systems in the control cabinet communicate with computer software allowing the signals to be linearized and fed to digitizing circuit boards within the computer. The computer software then determines the difference between the temperature set point and the input signal and adjusts the power feed (through a time proportioning algorithm) by switching on and off relays in the control cabinet [67].

The manikin is equipped with 187 artificial sweat glands located throughout its body, with the exception of its head, hands and feet. Water is metered to the sweat glands from a supply reservoir, placed on a balance located near the ceiling just outside of the environmental chamber. A computer controlled microvalve system in the manikin distributes the water each of the individual sweat glands [67]. The sweat glands are designed to continuously supply liquid water to the manikin to keep its 'skin' saturated throughout testing. The 'skin' consists of an inner nonwoven material which spreads the water to a larger area and outer microporous membrane [66]. Figure 3.4 shows the cross section of a sweat gland [66].




1 – water supply
2 – foam plastic shell
3 – heating wire
4 – isolating layer
5 – metal plating
6 – isolating layer
7 – skin material
8 – skin material
9 – net for abrasion protection

**Figure 3.4: Cross Sectional View of a Sweat Gland for the Sweating Manikin**

A one-shot technique that is typical of some sweating manikins is used to initially saturate the skin before testing. This technique is also used to saturate the head, hands, and feet where form-fitting cotton fabric materials are used as a makeshift skin to allow evaporative cooling in these areas. Once testing has begun, the rest of the manikin's sections are fed water via the valve system where individual valves are opened and closed to achieve the user-defined sweat rate (up to 300 g/m²·h). Before a series of testing, calibration software opens and closes each valve on a set interval and reads the weight of the precision water-supply scale before and after activating each valve. In this way, the computer can time proportion each valve's opening to supply the desired water delivery rate.

Figure 3.5 shows the manikin, environmental chamber, water supply and control system [66].

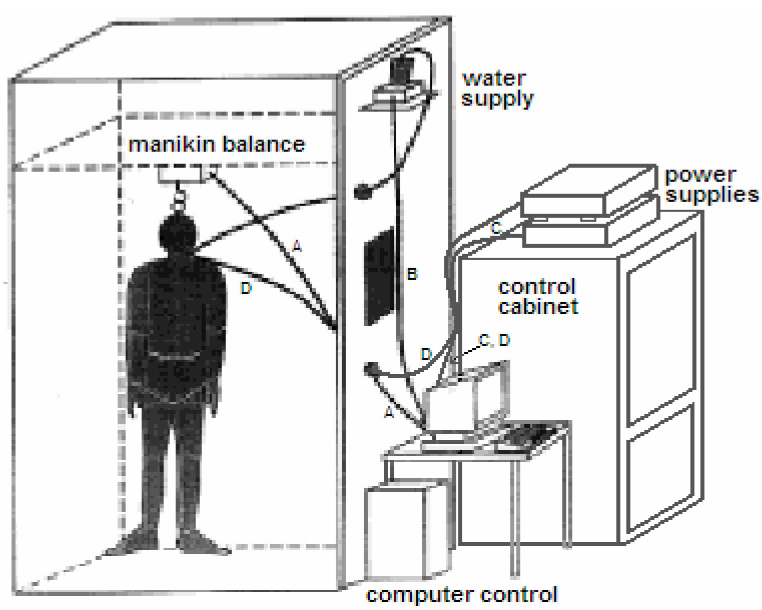



**Figure 3.5: Control System for Sweating Manikin in Environmental Chamber**

The control cabinet houses the necessary circuitry to make the manikin operate properly such as data acquisition components, voltage reducers, relays, resistors to draw current, switches, fuses, etc. The control cabinet acts an intermediary for all communication between the manikin and the computer. The precision scale (accurate to 0.001 g) that measures the water supply communicates directly with the computer to regulate the sweat rate. Separate from the control chamber and computer system, the manikin is suspended from a scale that gives a digital reading outside of the chamber accurate to 0.001 kg.

The manikin itself is modeled after a male size 40R and has prosthetic joints in the knees, hips, elbows and shoulders which allow the manikin to be dressed more easily and tested in various postures [67]. At this time, however, it cannot move on its own and thus all tests are static and cannot take into account effects of body motion. Although it is limited in this respect, its body is now powered by two separate sources reducing the load on one source which should help to improve the overall capability and variability of the system. Also, all body parts were calibrated and all necessary repairs were made to ensure that the manikin would function properly.

### 3.1.1 Dry Testing

Dry testing (for thermal insulation) was conducted following ASTM method F 1291-04 Standard Test Method for Measuring the Thermal Insulation of Clothing Using a Heated Manikin. However, the environmental conditions were modified from the standard in order to better represent the actual conditions used during the physiological trial (Warm Environment Protocol of the International Firefighter Protective Clothing Breathability Research Project). For this dry condition, the manikin testing was done at 25 ºC, 35% RH, since the manikin cannot be practically tested at 39 ºC since that is hotter than the manikin and he should never require power to maintain heat but instead gain heat. So, instead the 25 ºC condition was used and the insulation value was then used to predict what dry heat gain would be at 39 ºC. Also, the manikin was tested without the presence of wind blown across its body.

All garments, station uniforms, and accessories were preconditioned in the environmental chamber at the conditions they were to be tested for a minimum of 8 hours before testing. During the physiological trial, the garments had been conditioned in the lab (22 $\pm$ 1$^{o}$C, ~65% RH) before testing; however, for manikin testing, the garments were conditioned in the test conditions, so that the manikin could stabilize more quickly. Before and after each test the garment coats and trousers were weighed on a digital scale (accurate to 0.01 kg). This was done in order to get an average dry weight for the garments in these conditions. Because the manikin is heated at a higher temperature than the ambient air in which the garment was conditioned, moisture transfer is possible and so before and after weights were taken to get an average for the condition. Also, the inner liners (moisture barrier and thermal liner) were removed from the garment outer shell and weighed by themselves as had been done in the physiological trial. During six of the tests, station uniforms and all garment accessories were also weighed (three measurements for gear set A and three measurements for gear set B) in the same manner. These values were then used to calculate the average dry weight of the station uniforms and all accessories.

The order of the dry tests was randomized in order to be able to perform certain, statistical tests. Before and after each test, additional weights were recorded from the manikin scale (accurate to 0.001 kg) while dressing (undressing) the manikin. Weights were taken at dressing points that could be compared with data available from the physiological trial and/or the digital scale garment weights to establish the agreement between the scales. Table 3.1 shows the dressing points at which the manikin was weighed.

**Table 3.1: Scale Positions at which Weights were Recorded for Various States of Dress for Manikin Dry Testing**

| State of Dress | Scale Position | Weight |
|---|---|---|
| Nude | -10 | |
| + Underwear | -10 | |
| + Station Uniform / Socks | -10 | |
| + All Gear except Harness | -2 | |
| + Harness | +3 | |

Because the manikin scale can only weigh up to 4.000 kg, a counterbalance was used to offset the weight of the clothing exceeding that amount. It therefore had to be adjusted as the manikin was dressed in order to keep the scale within the range of its capability. The first scale position was chosen so as to keep the scale reading as close to zero as possible so that it would not have to be adjusted until the weight of the added clothes exceeded the scale's capable range. The other positions were also chosen close to zero so that the same positions could be used later in wet testing when the extra weight of the water was added. Thus, all manikin weights are relative, and must be adjusted according to the counterbalance for them to be meaningful. If absolute weights were desired, the weight of the manikin would also have to be considered since the scale must have been zeroed out with the manikin already suspended and the counterbalance only capable of handling the additional weight of clothing and not the manikin itself.

For dry testing, the experiment was always allowed some amount of time to stabilize before testing began. Once the temperatures and heating power of each section appeared to be fairly stable, testing was begun. This usually took between 45 minutes and an hour. Dry tests then lasted an additional hour; during the first thirty minute interval the manikin was allowed to continue to stabilize and then 'steady-state' temperature and power measurements were taken during the second thirty minute interval. Because there were usually small changes in the manikin weights just after dressing and when the experiment actually started, the manikin weights were also recorded when the experiment started and just after the experiment stopped in the case that he could not be undressed immediately.

During the experiment, the computer software recorded the skin temperature and power requirement for each manikin section as well as the room temperature around the manikin. The surface area of each manikin section was known. From this data, thermal resistance was then calculated by the parallel method according to the following equation:

$R_t = (T_s - T_a) \cdot A / H$, where

$R_t$ = total thermal resistance of the clothing ensemble and surface air layer (ºC·m²/W),

$A$ = area of the manikin's surface (m²),

$T_s$ = temperature at the manikin surface (ºC),

$T_a$ = temperature of the air surrounding the manikin (ºC), and

$H$ = power required to heat manikin (W) [68].

Because the manikin is divided into sections, the total power requirement had to be calculated as an area weighted sum of the individual section power requirements according to the following equation:

$$H = \sum_{i=1}^{18} H_i \cdot A_i, \text{ where}$$

$H$ = total power requirement (W),

$H_i$ = power requirement of $i^{th}$ section (W/m²), and

$A_i$ = area of $i^{th}$ section (m²).

Table 3.2 shows different manikin sections and their respective areas.

**Table 3.2: Manikin Surface Area by Section**

| ID | Section | Area (m²) |
|---|---|---|
| 1 | Upper Head | 0.051 |
| 2 | Chest | 0.173 |
| 3 | Back | 0.179 |
| 4 | Left Upper Arm | 0.104 |
| 5 | Left Lower Arm | 0.047 |
| 6 | Left Hand | 0.048 |
| 7 | Right Upper Arm | 0.104 |
| 8 | Right Lower Arm | 0.047 |
| 9 | Right Hand | 0.048 |
| 10 | Standing | 0.040 |
| 11 | Lower Torso | 0.181 |
| 12 | Right Thigh | 0.153 |
| 13 | Right Leg | 0.117 |
| 14 | Right Foot | 0.041 |
| 15 | Left Thigh | 0.153 |
| 16 | Left Leg | 0.118 |
| 17 | Left Foot | 0.041 |
| 18 | Lower Head | 0.074 |
| ***Total*** | | *1.719* |

The skin temperature of the manikin also had to similarly be calculated as an area weighted average of the individual section temperatures according to the following equation:

$$T_s = \sum_{i=1}^{18} (A_i / A) \cdot T_{si}, \text{ where}$$

$T_s$ = temperature at the manikin surface (ºC),

$A_i$ = area of $i^{th}$ section (m²),

$A$ = area of the manikin's surface (m²), and

$T_{si}$ = surface temperature of $i^{th}$ section (ºC).

Once these values were found, $R_T$ (parallel) was then calculated ($I_T$ in units of clo could also be calculated by multiplying $R_T$ by 6.45). The total amount of dry heat loss was also calculated by dividing the total power requirement (H) by the manikin's total surface area (A).

To estimate the amount of dry heat loss (gain) that would take place at 39 ºC (physiological trial conditions), a new power requirement was calculated based on the thermal resistance and the new temperature gradient according to the following equation:

$H_p = (T_s - T_{at}) \cdot A / R_t = (T_s - 39) \cdot 1.719 / R_t$, where

$H_p$ = estimated power requirement (W)

$T_s$ = temperature at the manikin surface (ºC),

$T_{at}$ = ambient temperature desired to predict heat loss for (ºC),

$A$ = area of the manikin's surface ($m^2$), and

$R_t$ = total thermal resistance of the clothing ensemble and surface air layer (ºC·$m^2$/W).

The predicted total amount of dry heat gain (-C) was then also calculated by dividing the total estimated (theoretical) power requirement ($H_p$) by the manikin's total surface area (A).

### 3.1.2 Wet Testing

Wet testing (for evaporative resistance) was done following proposed ASTM method F 2370 Standard Test Method for Measuring the Evaporative Resistance of Clothing Using a Sweating Manikin (Option 1). However, the environmental conditions were modified from the standard in order to better represent the actual conditions used during the physiological trial (Warm Environment Protocol of the International

Firefighter Protective Clothing Breathability Research Project). For this wet condition, the manikin testing was done at 35 ºC, 35% RH. It was attempted to test the manikin in the actual conditions (39 ºC, 35% RH) of the trial; however, these conditions could not be used because the manikin was not able to evaporate enough water from some sections of its body to keep it from rising in temperature above 35 ºC. This meant that no power was required for these areas and evaporative heat loss, however small it may have been, could not be measured. So, instead the 35 ºC condition was used and the evaporative resistance value was then used to predict what evaporative heat loss would be at 39 ºC. Also, the manikin was tested without the presence of wind blown across its body.

The overall process of conditioning, weighing, dressing, and testing the manikin for wet testing was very similar to that used for dry testing. As in the dry testing protocol, all garments, station uniforms, and accessories were conditioned in the environmental chamber at the conditions they were to be tested for a minimum of 8 hours before testing. Before and after each test the garment coats and trousers (as well as the separated inner liners) were weighed on a digital scale (accurate to 0.01 kg). Also, for each test, station uniforms and all garment accessories were also weighed in the same manner. This had to be done for every test since the accumulation of moisture in the garments is much more important and variable in wet testing than in dry testing. These values were then used to calculate the average weight gain rate of the station uniforms and all accessories. The gloves, socks, underwear, and hood were again weighed on a precision scale (accurate to 0.001 g), since they were lighter and within the scales calibrated range.

The order of the wet tests was the same as the order of dry tests when possible. However, occasionally test orders were switched around somewhat in order to be able to use properly conditioned gear. As in dry testing, additional weights from the manikin scale (accurate to 0.001kg) were also recorded before and after each test while dressing (undressing) the manikin. For the most part, weights were taken at the same dressing points that were used in dry testing; the only difference is that an extra weight was taken after the manikin had been initially wetted. Table 3.3 shows the new dressing points at which the manikin was weighed.

**Table 3.3: Scale Positions at which Weights were Recorded for Various States of Dress for Manikin Wet Testing**

| State of Dress | Scale Position | Weight |
|---|---|---|
| Nude | -10 | |
| + Water | -10 | |
| + Underwear | -10 | |
| + Station Uniform / Socks | -10 | |
| + All Gear except Harness | -2 | |
| + Harness | +3 | |

The scale position for each dressing point was kept the same as for its respective dry test point.

The key difference between dry and wet testing involved the wetting process. Before testing, drinking water (~1.75 L) was heated to approximately 35 ºC. This water was then transferred into a pressurized spray canister that was used to wet the manikin. After taking its nude weight, the manikin (now equipped with its cotton ‘skin’ for its head, hands, and feet) was sprayed as uniformly as possible until its entire surface was saturated. After spraying, a nude, saturated weight was taken and dressing then continued exactly as in dry testing.

Once the manikin was dressed and its final pretest weight recorded, the weight from the water supply scale (accurate to 0.001 g) was recorded and testing was begun. The sweat rate was set at 250.0 $g/m^2 \cdot hr$; sweating began as soon as testing started. The experiment length varied depending on how long it took for the temperature and heating power of each section to stabilize. Most tests ran between 75 and 85 minutes with 'steady-state' temperature and power measurements taken during the last thirty minute interval of the test. Though most tests took less than 1.5 hours, a maximum experiment length was set at 2.5 hours, where if a test had not reached steady-state by then it would be aborted. After the test period was over, the final water supply scale weight was taken and the manikin was then undressed and weighed exactly as in the dry testing protocol. Whenever possible, the manikin was allowed to dry between tests; however, because of time constraints, occasionally it could not be completely dried. In the case that the manikin could not be dried, its nude weight was still recorded before and after wetting and special care was taken not to over-saturate the manikin upon rewetting.

During the experiment, as in dry testing, the computer software recorded the skin temperature and power requirement for each manikin section as well as the room temperature around the manikin. From this data, evaporative resistance was then calculated by the parallel method according to the following equation:

$R_{et} = [(P_s - P_a) \cdot A] / [H_e - (T_s - T_a) \cdot A / R_t]$, where

$R_{et}$ = total evaporative resistance of clothing ensemble and air layer (kPa·m²/W),

$P_s$ = water vapor pressure at the manikin's sweating surface (kPa),

$P_a$ = water vapor pressure in the air surrounding the clothing (kPa),

$A$ = area of the manikin's surface that is sweating (m²),

$H_e$ = power required for sweating areas (W),

$T_s$ = temperature at the manikin surface (ºC),

$T_a$ = temperature of the air surrounding the manikin (ºC), and

$R_t$ = total thermal resistance of the clothing ensemble and surface air layer (ºC·m²/W) [69].

Because the manikin is divided into sections, the total power requirement had to be calculated as an area weighted sum of the individual section power requirements according to the following equation:

$$H_e = \sum_{i=1}^{18} H_{ei} \cdot A_i, \text{ where}$$

$H_e$ = total power requirement (W),

$H_{ei}$ = power requirement of $i^{th}$ section (W/m²), and

$A_i$ = area of $i^{th}$ section (m²).

The skin temperature of the manikin, as in dry testing, also had to be calculated as an area weighted average of the individual section temperatures according to the following equation:

$$T_s = \sum_{i=1}^{18} (A_i / A) \cdot T_{si}, \text{ where}$$

$T_s$ = temperature at the manikin surface (ºC),

$A_i$ = area of $i^{th}$ section (m²),

$A$ = area of the manikin's surface (m²), and

$T_{si}$ = surface temperature of $i^{th}$ section (ºC).

The vapor pressure at the manikin's skin and the ambient air were calculated as functions of the relative humidity and temperature at each location. In order to calculate the vapor pressure, the saturation vapor pressure first had to be determined. The saturation vapor pressure was calculated from the temperature according to the 6th Order Polynomial model (developed by Flatau, et. al in 1992) [70]. It was chosen to use this model since it was valid in the range of the temperatures used and yielded values which agreed well with the vapor pressure differential used for standard conditions in the ASTM F 1868 evaporative resistance standard [57, 70]. The saturation vapor pressure was thus calculated according to the following equation:

$e_s = a_1 + a_2 \cdot T^1 + a_3 \cdot T^2 + a_4 \cdot T^3 + a_5 \cdot T^4 + a_6 \cdot T^5 + a_7 \cdot T^6$, where

$e_s$ = saturation vapor pressure (mb),

$T$ = temperature (ºC),

$a_1$ = 6.11176750,

$a_2$ = 0.443986062,

$a_3$ = 0.143053301E-01,

$a_4$ = 0.265027242E-03,

$a_5$ = 0.302246994E-05,

$a_6$ = 0.203886313E-07, and

$a_7$ = 0.638780966E-10 [70].

Once the saturation vapor pressure was calculated, the actual vapor pressure could be calculated using the relative humidity according to the following equation:

$P = (RH*e_s)/100$, where $P$ = water vapor pressure (mb),

$RH$ = relative humidity (%), and

$e_s$ = saturation vapor pressure (mb)

Once the vapor pressure was found, it was then divided by 10 to convert it into units of kPa in order to be compatible with the evaporative resistance formula.  In calculating the vapor pressure at the manikin's skin, the relative humidity was assumed to be 100% since the skin should be saturated.

Once these values were found, $R_{et}$ (parallel) was then calculated (permeability index ($I_m$) could also be calculated by multiplying ($R_T/R_{et}$) by 0.061).  The total amount of dry heat loss was also calculated by dividing the total power requirement for the wet test ($H_e$) by the manikin's total surface area (A).

To estimate the amount of evaporative heat loss that would take place at 39 ºC (physiological trial conditions), a new power requirement was calculated based on the thermal resistance and evaporative resistances and the new temperature and pressure gradients according to the following equation:

$H_{ep}$ $= [(P_s – P_a) \cdot A / R_{et}] + [(T_s – T_a) \cdot A / R_t]$

$= [(Ps – 2.449) \cdot 1.719 / R_{et}] + [(T_s – 39) \cdot 1.719 / R_t]$, where

$H_{ep}$ = estimated power requirement,

$P_s$ = water vapor pressure at the manikin's sweating surface (kPa),

$P_a$ = water vapor pressure in the ambient air desired to predict heat loss for (kPa),

A = area of the manikin's surface that is sweating (m²),

$R_{et}$ = total evaporative resistance of clothing ensemble and air layer (kPa·m²/W),

$T_s$ = temperature at the manikin surface (ºC),

$T_a$ = ambient temperature desired to predict heat loss for (ºC), and

$R_t$ = total thermal resistance of the clothing ensemble and surface air layer (ºC·m²/W).

The theoretical amount of total heat loss ($Q_t$) was then calculated by dividing the total estimated power requirement ($H_{ep}$) by the manikin's total surface area (A). Finally the theoretical amount of evaporative heat loss (E) possible at 39 ºC was determined by adding the dry heat gain to the total heat loss ($Q_t – C$).

## 3.2 Clothing Materials

Clothing materials refer to the 6 different garments tested as well as the station uniforms and garment accessories. All clothing materials were chosen to match as closely as possible those used in the physiological wear trial to which the manikin data will be compared. Figures 3.6 and 3.7 show the fully-dressed manikin in one of the test garments from the front (9) and from the side (10).

**Figure 3.6: Front View of Fully Dressed Manikin**

**Figure 3.7: Side View of Fully Dressed Manikin**

### 3.2.1 Turnout Garments

The 6 garments worn in manikin testing were some of the actual garments used in the physiological trial. These garments were all constructed of a common shell and were manufactured to the same design. The design used was a very simple, traditional design.

The coat was a size 44 regular, regular length with no tail. It uses a zipper and Velcro front closure system attached to a T-shaped collar that also closes with Velcro. It has two pockets (one on each side) located near the waist. 3" trim surrounds the bottom of the coat near the waist, the middle of the coat near the sternum, and each sleeve around the forearm. The pants are a size 38/30 and also use a very traditional design. They are held up by a system of adjustable waist straps and suspenders. They also have a zipper and Velcro closure system at the fly. There are two pockets (one on each leg) just below the coat. 3" trim surrounds each leg near the ankle. No extra padding was used in either the coat or the pants of the garment. Table 3.4 shows the different combinations of outer shells, moisture barriers, and thermal liners that were used in each of the garments.

**Table 3.4: Outer Shell, Moisture Barrier, and Thermal Liner Construction for Garments 1-6**

| Garment Identification | Outer Shell | Moisture Barrier | Thermal Liner |
|---|---|---|---|
| **1** | A | A | A |
| **2** | A | A | B |
| **3** | A | B | B |
| **4** | A | C | B |
| **5** | A | A | C |
| **6** | A | B | A |

The garments materials were chosen to achieve a substantial range of THL values, as measured on the hot plate. In order to achieve these differences, the outer shell used for each garment was the same while the moisture barrier and thermal liner were varied. Moisture barrier A and B represent ‘breathable’ moisture barrier technologies while moisture barrier C represents a ‘non-breathable’ technology. In terms of vapor permeability of the moisture barriers, A > B > C. The most significant difference between the thermal liners used was in their insulation values. In terms of the insulation values of the thermal liners, A ~ C > B.

For testing, the garment was worn just as it would be during a structural firefighting scenario and just as it had been in the physiological trial with a few, minor exceptions. To simulate how the subjects in the physiological trial were dressed, the manikin used sneaker-type shoes instead of boots. The leg was taped around the trim as it had been in the physiological trial. Also, as in the physiological trial, the regulator was not hooked up to the facepiece allowing area around the nose and mouth to be exposed to the ambient air. Some other slight modifications were made to the garment accessories in order to fit them to the manikin. These modifications are detailed in the following sections.

### 3.2.2 Station Uniform

The station uniforms worn for manikin testing were the same as those used in the NCSU physiological trial. Two station uniforms were made available so that one could always be conditioning while the other was being worn.

*Station Shirt*

The station shirt is a typical, button-up, woven, short-sleeve station shirt constructed of 55% FFR (Fibrous Flame Retardant Fiber) and 45% cotton. The station shirt fitted to the manikin is a size large (16 16½).

*Station Pants*

The station pants are typical, zipper fly, woven station pants constructed of 55% FFR and 45% cotton. The pants fitted to the manikin are a size 36 regular and include a belt.

### 3.2.3 Garment Accessories

All garment accessories dressed on the manikin were chosen to match, as closely as reasonably possible, those which were used in Warm Environment Protocol of the International Firefighter Protective Clothing Breathability Research Project. For many items, the exact materials as used in this project were available to be used. In some cases, these materials had to be modified in order to fit the manikin. In a few cases the exact accessories could not be located, or for some reason, could not be used and a very similarly constructed accessory was used instead. For each accessory, there were two sets available (with the exception of the helmet) so that one could always be conditioning while the other was being worn. Only one helmet was modified to fit the manikin because of the difficulty in modifying a second helmet in the same fashion as the first and the time/cost it takes to modify a helmet.

*Helmet*

The helmet used for manikin testing was one which was very similar to the one used during the physiological wear trial.  The helmet used in the physiological wear trial was constructed as follows:

Nomex chin strap with quick release buckle and slide fastener

4” hard-coated polycarbonate faceshield with mounting hardware

Retro-reflective fluorescent, adhesive backed strips

Rip-Stop PBI/Kevlar ear/neck protector

Inner crown system including:  Prevex inner shell, ratchet headband, flannel brow pad, urethane impact liner, 6-point nylon crown strap assembly, and Velcro strips

Fiberglass helmet shell

A similar helmet was used in the manikin testing constructed as follows:

Nomex chin strap with quick release buckle and slide fastener

Retro-reflective fluorescent, adhesive backed strips

Rip-Stop PBI/Kevlar ear/neck protector

Inner crown system including:  Polymer inner shell, ratchet head band, leather brow pad, foam impact liner, 6-point nylon crown strap assembly with cloth pad, and Velcro strips

Fiberglass-reinforced Kevlar helmet shell

The materials, though they varied slightly, should be sufficiently similar to assume a negligible impact on heat and moisture transport through the helmet system. Though the flannel brow pad could be expected to absorb more moisture than the leather pad used in the manikin tests, the difference should be minimal. There is some cloth in the leather assembly, as well as the cloth pad incorporated in the manikin-test helmet's crown strap assembly, that should help to negate any differences in absorption. The construction, otherwise, is very similar with the exception of the facepiece. The helmet used in the physiological trials used a polycarbonate faceshield, while the helmet used for manikin testing used a goggle system for face protection. This difference, however, should be naught since the faceshield is not in intimate contact with any air permeable part of the clothing system. The goggles were thus not included in the manikin testing.

Some modifications had to be made in order to fit the helmet onto the manikin. The manikin is suspended by a hook structure at the top of its head. To fit the helmet onto the head, a hole thus had to be made in the top center of the helmet. To avoid damaging the manikin by taking it on and off of the hook assembly a slit also had to be cut through the shell and inner components of the helmet leading to the central aperture. The ear flap, cloth pad of the nylon crown strap assembly, and ratchet head band also had to be cut to allow it to be fit onto the manikin. The outer shell and central aperture were cut using a combination of a hand saw and cutting shears, while the rest of the components were cut using either a razor blade or scissors. Duct and electrical tape were applied to the edges of the slit in the shell and inner components to keep them neat and held together securely. Once on the manikin, duct tape was used to seal the gap created in the helmets shell. The ratchet system was cut in such a way that it could be pulled apart and ratcheted back together without further modification. Velcro was attached to either side of the slit in the ear flap to hold it together as it should be, once donned.

*Hood*

The hood used for manikin testing was one which was very similar to the one used during the physiological wear trial. The hood used in the physiological wear trial was a 20% PBI / 80% Lenzing 2-ply balaclava hood. The hood used for manikin testing was a PBI 2-ply balaclava hood. Though the constituent materials differed somewhat, the design was identical and the weight difference was less than 0.1 kg.

Because of the suspension (top of the head) and wiring (back of the neck) system, some modification had to be done to the hood. The hood was cut vertically from the back to the top of the head. A zipper was sewn along the majority of this opening from the base of the neck to the top of the head. Once donned, duct tape was applied around the very top to eliminate any gaps between the hook suspension system and the hood. Duct tape was also applied at the bottom portion of the slit and around the wiring system to void the gaps there.

*Facepiece Assembly (SCBA Mask)*

The Self Contained Breathing Apparatus (SCBA) mask used in the manikin testing was the exact model used in the physiological trial. It was a typical firefighting full facepiece assembly with the facepiece constructed of ethylene propylene diene monomer (EPDM) rubber including a chin cup and nose cup. The lens in the facepiece was molded of polycarbonate plastic. The head harness was constructed of Kevlar mesh and attached to the top of the facepiece with two button snaps on either side of the head. The head harness pulled the facemask tight against the head via two lower Kevlar neck straps and two upper Kevlar temple straps.

Slight modifications were made to the facepiece assembly in order to fit it to the manikin. Loops on the neck and temple straps (by the manikin's left ear) were removed so that the facepiece could be fit around the manikin's face rather than pulling the assembly over the head. With the loops cut off, the straps could be unfastened and refastened to the facepiece assembly. Electrical tape was used to keep the Kevlar fabric from fraying where it was cut, since it could not be singed. Also, the Kevlar mesh on the head harness was slit down the center from the front of the head harness to the crown of the head to allow it to fit around the hook suspension system.

*SCBA Harness*

The Self Contained Breathing Apparatus (SCBA) harness used in the manikin testing was the exact model used in the physiological trial. It was a typical SCBA harness constructed as a one-piece aluminum alloy frame designed to fit along the shape of the back. The design incorporated wide-bodied shoulder and hip pads constructed of heavy braided para-aramid webbing. It was equipped with fairly standard gear for the fire industry including a pressure gauge, pressure reducer, regulator assembly with holder, hose assembly, alarm console, valve assembly, and cylinder latch. The cylinder itself was removed for the manikin testing for greater ease in donning and doffing and thus less wear and tear on the manikin. No other modifications were made to the harness. The weights of the harnesses used in each of the two gear sets were slightly different from one another because of a difference in the size of the pressure reducer on each harness.

### *Shoes*

During the physiological trial, subjects brought in their own sneaker-type shoes which fit their feet. Since each subject's shoes differed, a plain, generic sneaker-type shoe was chosen to fit the manikin. The shoe chosen was a US size 11 men's shoe, with Velcro straps for ease of donning and doffing. No modifications were necessary to fit the shoes to the manikin.

### *Socks*

The socks worn in the physiological trial were cotton (>85%) either crew or tube style socks. The socks dressed on the manikin were 89% cotton, 9% polyester, 1% nylon, 1 % spandex crew-style socks. Some of the elastic at the top of the sock was removed in order to more easily dress the socks on the manikin.

### *Underwear*

The underwear used in the physiological trial was 100% cotton underwear fit to each subject. The underwear used for the manikin testing was likewise was 100% cotton underwear fit to the manikin (size 36). No modifications were necessary.

*Gloves*

The NFPA compliant gloves used in the manikin testing were some of the actual gloves used in the physiological trial. They were constructed of fire retardant, heat resistant cowhide leather shell attached to a PolyTetraFluoroEthylene (PTFE) film laminated to Vilene that acted as the moisture barrier. The glove also included a Nomex wristlet.

The gloves had to be modified in order to fit the hands of the manikin. The inner liner was carefully detached from the outer shell. The section of the outer shell covering the ring and middle fingers was removed and the remainder was sewn together making a mitten style outer shell. The outer shell was also partly detached from the wristlet across the top portion (back of the hand) and a slit was cut from the base of the glove to the middle of the hand along the center axis of the back of the hand. Velcro was attached to either side of the slit in the outer shell to hold it together as it should be, once donned. To don the glove, the inner liner was first fit on the hand with each finger in place and the outer mitten was then fit around the inner liner and Velcro attached.

### 3.3 Hot Plate Testing

The evaporative resistance, thermal resistance, and total heat loss values from the hot plate were available for each of the six garments. These same materials had been tested as part of the International Firefighter Protective Clothing Breathability Research Project on NCSU's guarded sweating hot plate.

The hot plate used was a Holometrix Model TCB-TX housed in Tenney Engineering, Inc. Model T-30RC environmental test chamber. The Holometrix system included a separate cabinet which was used to control the hot plate; the Tenney system included the VersaTenn control system to control the environmental chamber. ThermDAC v6.1, a thermal data acquisition and control system, developed by Northwest Measurement Technology, was the software used to measure the necessary parameters, communicate with the hot plate, and calculate the thermal and evaporative resistances.

Important specifications about the hot plate include:

9.88" square inner plate (surrounded by a 0.12" uniform gap all around) and heater

30" guard heater surrounding the main (inner)

Bucking heater located beneath the main heater

20" by 20" test sample area

Porous surface plate

Continuous water feed system

Fan system creating wind across (parallel to) the test samples

Figures 3.8 and 3.9 show the hot plate in its environmental chamber (11) and close up (12).

**Figure 3.8: Hot Plate in Environmental Chamber**

**Figure 3.9: Close-Up View of the Sweating Hot Plate**

### 3.4 Physiological Testing

Data was made available from the International Firefighter Protective Clothing Breathability Research Project (physiological trial) conducted at NCSU. The garments, station uniforms and accessories worn during the physiological trial are described alongside those used for manikin testing under the appropriate sections. The testing was done in a state-of-the-art climate controlled chamber (maintained by Environmental Specialties, Inc.) in the Center for Research on Textile Protection and Comfort (T-PACC) laboratory at NCSU. The chamber is the same one in which manikin the manikin testing was carried out. Treadmills, adjustable for speed and incline, were located inside of the chamber where subjects walked on them according to protocol. Measurement equipment included: an EKG heart rate monitor, skin thermistors (Yellow Springs Instruments series 400), a rectal thermistor (Yellow Springs Instruments series 400 disposable probe), a humidity sensor probe, and a digital scale [48]. Figures 3.10

and 3.11 show subjects dressed and exercising in the turnout garments evaluated during the wear trial.

**Figure 3.10: Subject Dressed for the Warm Environment Protocol**

**Figure 3.11: Subject Exercising During the Warm Environment Protocol**

Further details about the study and its protocol are available in Chapter 2 of this work and/or elsewhere [42, 43, 48].

# Chapter 4: Results and Discussion

## 4.1 Material Property Results

Material properties were determined from both available data and measurement. Composite thickness, composite weight, and all hot plate data were made available from the International Firefighter Protective Clothing Breathability Research Project, which evaluated the same turnout systems. Manikin data was measured according to the methods described in Chapter 3.

### 4.1.1 Material Weights

Composite thicknesses and weights were available from the Breathability Research Project; all of the garment weight data reported here was measured during dry testing and determined by averaging the weights of conditioned garments before and after testing for three tests (a total of six measurements). Table 4.1 shows the composite weight and thickness as well as the turnout weights.

**Table 4.1: Dry System Weights**

| Garment System | Dry System Weights | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Composite | | Garment | | | | | |
| | Weight ($oz/yd^2$) | Thickness (mm) | Turnout (kg) | Turnout Pants (kg) | Turnout Coat (kg) | Turnout Liner (kg) | Pants Liner (kg) | Coat Liner (kg) |
| 1 | 19.95 | 4.98 | 3.89 | 1.82 | 2.08 | 1.50 | 0.74 | 0.77 |
| 2 | 19.59 | 5.28 | 3.88 | 1.82 | 2.07 | 1.49 | 0.74 | 0.76 |
| 3 | 19.82 | 5.08 | 3.91 | 1.84 | 2.08 | 1.52 | 0.75 | 0.77 |
| 4 | 27.25 | 4.17 | 4.67 | 2.10 | 2.56 | 2.09 | 0.98 | 1.11 |
| 5 | 19.51 | 4.9 | 3.89 | 1.81 | 2.08 | 1.50 | 0.73 | 0.77 |
| 6 | 20.19 | 4.88 | 3.96 | 1.85 | 2.11 | 1.57 | 0.77 | 0.80 |

The liner weights refer to the weight of the moisture barrier and thermal liner removed from the outer shell. The outer shell weights could be determined by subtracting the liner weights from the turnout weights, but also include trim, pockets, wristlets, other design features, and some amount of liner material around the interfaces where the liner is attached. Weights were also measured and recorded for each of the garment accessories in a similar fashion. Table 4.2 shows the weights of the accessories.

**Table 4.2: Accessory Weights**

| Accessory | Accessory Weights (Dry) | | |
|---|---|---|---|
| | Morning Gear (kg) | Afternoon Gear (kg) | Average (kg) |
| Left Glove | 0.170 | 0.170 | 0.170 |
| Right Glove | 0.170 | 0.177 | 0.173 |
| Helmet | 1.185 | 1.185 | 1.185 |
| Harness | 4.810 | 4.703 | 4.757 |
| Hood | 0.130 | 0.130 | 0.130 |
| SCBA Mask | 0.590 | 0.590 | 0.590 |
| Left Shoe | 0.363 | 0.368 | 0.365 |
| Right Shoe | 0.365 | 0.370 | 0.368 |
| Left Sock | 0.030 | 0.030 | 0.030 |
| Right Sock | 0.030 | 0.030 | 0.030 |
| Station Pants | 0.680 | 0.700 | 0.690 |
| Station Shirt | 0.327 | 0.328 | 0.328 |
| Underwear | 0.064 | 0.060 | 0.062 |
| Station Uniform | 1.002 | 1.030 | 1.016 |
| Socks and Underwear | 0.130 | 0.123 | 0.126 |
| Total | 8.915 | 8.845 | 8.880 |

Two sets of accessories were used to ensure that one set could always be properly conditioned for testing more than one garment in a day. Weights were measured for each set of accessories, as designated by when they were expected to be used; data from both sets, and their average is reported in Table 4.2.

### 4.1.2 Hot Plate Data

Heat transfer properties of the various fabric composites were measured by the sweating hot plate as part of the Breathability Research Project. Specifics of the testing involved are described in Chapter 2. Table 4.3 shows the average thermal and apparent evaporative resistances of the fabric and air layer ($R_{ct}$ and $R_{et}$) as well as the thermal and evaporative resistances of the fabric on its own with the bare plate resistance subtracted out ($R_{cf}$ and $R_{ef}$); it also shows the heat losses predicted for the 'standard' (ASTM F 1868 Part C) conditions and the 'wear trial' (Warm Environment Protocol of the International Firefighter Protective Clothing Breathability Research Project) conditions.

**Table 4.3: Hot Plate Heat Transfer Data**

| Garment System | Hot Plate | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Intrinsic | | | | Standard Conditions (25ºC, 65% RH) | | | Wear Trial Conditions (39ºC, 35% RH) | | |
| | $R_{cf}$ | $AR_{ef}$ | $R_{ct}$ | $AR_{et}$ | THL ($Q_t$) | C | E | THL ($Q_t$) | C | E |
| 1 | 0.118 | 0.016 | 0.188 | 0.022 | 250.55 | 63.17 | 185.27 | 167.94 | -33.81 | 201.75 |
| 2 | 0.152 | 0.017 | 0.223 | 0.024 | 222.28 | 51.95 | 170.60 | 156.34 | -26.24 | 182.58 |
| 3 | 0.161 | 0.034 | 0.231 | 0.040 | 146.01 | 49.85 | 97.04 | 70.70 | -24.91 | 95.61 |
| 4 | 0.134 | 0.086 | 0.204 | 0.093 | 97.41 | 57.47 | 39.75 | 7.01 | -29.85 | 36.86 |
| 5 | 0.115 | 0.016 | 0.185 | 0.022 | 247.05 | 64.42 | 182.22 | 163.01 | -34.72 | 197.73 |
| 6 | 0.118 | 0.034 | 0.188 | 0.040 | 158.16 | 63.49 | 94.91 | 59.19 | -34.06 | 93.25 |

Thermal and evaporative resistances, as well as THL for the standard conditions, were reported in the Breathability Research Project. Other values were calculated from these values by determining the bare plate values that were used and computing heat losses for the desired conditions.

### 4.1.3 Manikin Heat Transfer Data

Heat transfer properties measured by the sweating thermal manikin were determined according to the procedure outlined in Chapter 3. A minimum of three wet and three dry tests were performed for each of the garments in order to calculate the various resistances and predicted amounts of heat loss. Table 4.4 shows the average thermal and evaporative resistances as well as heat losses predicted for same 'standard' and 'wear trial' conditions reported in Table 4.3.

**Table 4.4: Manikin Heat Transfer Data**

| Garment System | Manikin | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | Intrinsic | | | Standard Conditions (25ºC, 65% RH) | | | Wear Trial Conditions (39ºC, 35% RH) | | |
| | $R_t$ | $R_{et}$ | $R_{et}$ (Option2) | THL ($Q_t$) | C | E | THL ($Q_t$) | C | E |
| 1 | 0.337 | 0.095 | 0.108 | 67.29 | 29.69 | 37.60 | 21.65 | -11.90 | 33.55 |
| 2 | 0.333 | 0.094 | 0.114 | 68.16 | 30.14 | 38.02 | 21.98 | -12.06 | 34.04 |
| 3 | 0.321 | 0.105 | 0.121 | 68.27 | 31.27 | 37.00 | 17.94 | -12.41 | 30.35 |
| 4 | 0.348 | 0.407 | 0.361 | 39.18 | 28.71 | 10.47 | -2.98 | -11.58 | 8.60 |
| 5 | 0.332 | 0.091 | 0.108 | 73.80 | 30.16 | 43.64 | 23.29 | -12.03 | 35.33 |
| 6 | 0.355 | 0.100 | 0.109 | 66.40 | 28.13 | 38.28 | 20.68 | -11.29 | 31.96 |

The 'Option 2' method of calculating evaporative resistance refers to the 'Option 2' method described in the proposed ASTM method F 2370 Standard Test Method for Measuring the Evaporative Resistance of Clothing Using a Sweating Manikin which uses evaporation rate rather then power requirements to calculate the evaporative resistance. The purpose of its inclusion is mostly to complement the results from the 'Option 1' method which has been more extensively validated for the manikin used. Statistical significances for all relevant results were determined by Fisher's Least Significant Difference Test and Tukey's Honest Significant Difference Test and are reported in the appendix of this work.

### 4.2 Weight Change Results for Wet Testing with the Sweating Manikin

During wet testing, manikin, gear, and water supply weights were recorded before and after each test in order to determine the amount of sweat, evaporation, and accumulation that occurred for each garment. Weight gains were recorded for each piece of the gear in order to determine any differences that might exist in where the moisture was accumulating. During wet testing most tests ran for 86 minutes; tests which ran longer or shorter than 86 minutes were repeated until 3 tests had been run for each garment at 86 minutes (± 1 minute) in order to achieve the most analogous results possible for changes in weight.

#### 4.2.1 Weight Changes Measured by Manikin and Water Supply Scales

Weight changes were recorded both on the manikin using the manikin scale and water supply scale and in the gear, once undressed, using a digital scale. Table 4.5 shows aspects of sweat, evaporation, and accumulation as measured by the manikin scale and water supply scale.

**Table 4.5: Moisture Transfer in Manikin**

| Garment System | Moisture Transfer in Manikin | | | | | | |
|---|---|---|---|---|---|---|---|
| | Total Evaporated (g) | Evaporation Rate (g/h) | Water Sprayed (g) | Water Fed (g/h) | Equivalent Sweat Rate (g/h) | % Sweat Evaporated | Accumulation in Gear (g) |
| 1 | 128.53 | 89.67 | 1005.61 | 510.53 | 1212.11 | 7.40 | 865.67 |
| 2 | 122.36 | 85.04 | 982.65 | 514.02 | 1196.95 | 7.10 | 855.33 |
| 3 | 114.99 | 80.22 | 962.93 | 511.32 | 1183.13 | 6.79 | 855.67 |
| 4 | 39.29 | 27.41 | 994.52 | 509.96 | 1203.81 | 2.28 | 930.33 |
| 5 | 128.61 | 89.73 | 1029.00 | 509.61 | 1227.52 | 7.33 | 874.67 |
| 6 | 127.00 | 88.25 | 923.84 | 513.34 | 1155.39 | 7.64 | 879.00 |

As with the material properties, statistical comparisons for the various weight change data can be found in the appendix.

In addition to measuring the sweat, evaporation, and accumulation, the manikin and water supply scales were used to measure the weight loss at various states of dress as described in Chapter 3. Table 4.6 shows the weight losses measured at these various states of dress for each garment.

**Table 4.6: Manikin Weight Loss Measured by Manikin Scale and Water Supply Scale**

| Garment System | Manikin Weight Loss | | | | |
|---|---|---|---|---|---|
| | Nude (kg) | In Underwear (kg) | In Station Uniform, Socks, and Underwear (kg) | In All Gear Except Harness (kg) | Fully Dressed (kg) |
| 1 | 0.994 | 0.902 | 0.394 | 0.124 | 0.129 |
| 2 | 0.978 | 0.876 | 0.356 | 0.119 | 0.122 |
| 3 | 0.971 | 0.867 | 0.351 | 0.126 | 0.115 |
| 4 | 0.970 | 0.855 | 0.309 | 0.049 | 0.039 |
| 5 | 1.003 | 0.905 | 0.389 | 0.134 | 0.129 |
| 6 | 1.006 | 0.877 | 0.366 | 0.121 | 0.127 |

In some instances, weight loss fully clothed was measured as being greater than the weight loss with the harness. Because the harness picked up little to no water in almost all cases, the numbers should be approximately equal or slightly lower for the fully dressed state. The slight discrepancies here are most likely due to error in the measurement system attributed to the counterweight system of measurement for the manikin scale described in Chapter 3. For this reason, it is expected that there is some error in the accuracy of the manikin scale. Particularly, though it is capable of measuring more precisely than the digital scale used to measure the turnout gear, repositioning of the counterweight throughout testing likely reduced the overall accuracy of the manikin scale somewhat. Weight losses measured at the same scale positions would be expected to have the least error, but if the weight of the counterweight was slightly off or notch positions were not completely accurate, somewhat larger differences could be expected when comparing weights measured in different scale positions. The error here would be a combination of error in the precise repositioning of the counterweight as well as error in the actual weight of the counterweight or calibrated notches for positioning the weight.

### 4.2.2 Weight Changes in Gear Measured with a Digital Scale

Weight gain in each component of the turnout gear was also measured but was done so with a calibrated digital scale that does not involve repositioning of a counterweight. The weight gain measured with this scale, thus, is expected to have better accuracy although the scale is not as precise (only measures to 0.01 kg). Table 4.7 shows the average weight gains of the turnout components measured on this scale.

**Table 4.7: Weight Gain in Turnout Gear**

| Garment System | **Weight Gain in Turnout Gear** | | | | | |
|---|---|---|---|---|---|---|
| | Turnout (kg) | Turnout Coat (kg) | Turnout Pants (kg) | Turnout Liner (kg) | Coat Liner (kg) | Pant Liner (kg) |
| 1 | 0.115 | 0.060 | 0.057 | 0.060 | 0.032 | 0.025 |
| 2 | 0.107 | 0.050 | 0.057 | 0.047 | 0.030 | 0.017 |
| 3 | 0.093 | 0.047 | 0.043 | 0.040 | 0.020 | 0.017 |
| 4 | 0.137 | 0.073 | 0.060 | 0.083 | 0.053 | 0.030 |
| 5 | 0.117 | 0.053 | 0.060 | 0.053 | 0.030 | 0.025 |
| 6 | 0.122 | 0.063 | 0.057 | 0.057 | 0.037 | 0.023 |

The turnout liners refer to the same components of the liner as described earlier and, also as described earlier, outer shell weight gains can be determined by subtracting the liner weight gain from the turnout weight gain. Accessory weight gains were also determined for each turnout. Table 4.8 shows the average weight gain for each turnout accessory.

**Table 4.8: Accessory Weight Gain by Garment Worn**

| **Accessory Weight Gain By Garment Worn** | | | | | | |
|---|---|---|---|---|---|---|
| | Garment | | | | | |
| Accessory | 1 | 2 | 3 | 4 | 5 | 6 |
| Station Uniform | 0.353 | 0.377 | 0.373 | 0.390 | 0.360 | 0.353 |
| Station Shirt | 0.143 | 0.147 | 0.140 | 0.187 | 0.140 | 0.135 |
| Station Pants | 0.213 | 0.233 | 0.233 | 0.242 | 0.220 | 0.223 |
| Gloves | 0.030 | 0.020 | 0.022 | 0.023 | 0.027 | 0.020 |
| Left Glove | 0.015 | 0.010 | 0.010 | 0.017 | 0.013 | 0.010 |
| Right Glove | 0.015 | 0.010 | 0.012 | 0.007 | 0.013 | 0.010 |
| Hood | 0.018 | 0.020 | 0.020 | 0.020 | 0.020 | 0.020 |
| Socks | 0.083 | 0.095 | 0.083 | 0.092 | 0.090 | 0.080 |
| Left Sock | 0.040 | 0.047 | 0.042 | 0.047 | 0.047 | 0.040 |
| Right Sock | 0.043 | 0.048 | 0.042 | 0.045 | 0.043 | 0.040 |
| Underwear | 0.055 | 0.053 | 0.055 | 0.055 | 0.058 | 0.055 |
| Helmet | 0.007 | 0.003 | 0.000 | 0.003 | 0.000 | 0.003 |
| Harness | 0.003 | 0.005 | 0.003 | 0.002 | 0.007 | 0.000 |
| Mask | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 |
| Shoes | 0.020 | 0.022 | 0.023 | 0.020 | 0.013 | 0.013 |
| Left Shoe | 0.010 | 0.012 | 0.010 | 0.013 | 0.010 | 0.003 |
| Right Shoe | 0.010 | 0.010 | 0.013 | 0.007 | 0.003 | 0.010 |
| All Accessories | 0.212 | 0.208 | 0.198 | 0.213 | 0.203 | 0.190 |

Weight gains were also calculated for turnout gear corresponding to the gear worn at each of the states of dress described in Chapter 3. Table 4.9 shows the average weight gain for the gear worn for each of these states of dress.

**Table 4.9: Weight Gain in Turnout Gear**

| | Turnout Gear Weight Gain | | | | |
|---|---|---|---|---|---|
| | Underwear (kg) | Socks and Underwear (kg) | Station Uniform, Socks, and Underwear (kg) | All Gear Except Harness (kg) | Full Ensemble (kg) |
| 1 | 0.055 | 0.137 | 0.490 | 0.680 | 0.683 |
| 2 | 0.053 | 0.143 | 0.520 | 0.692 | 0.697 |
| 3 | 0.055 | 0.133 | 0.507 | 0.665 | 0.668 |
| 4 | 0.055 | 0.147 | 0.537 | 0.740 | 0.742 |
| 5 | 0.058 | 0.143 | 0.503 | 0.680 | 0.687 |
| 6 | 0.055 | 0.133 | 0.487 | 0.665 | 0.665 |

Differences in the accumulation in gear reported in Table 4.5 and the weight gain of the full ensemble reported in Table 4.9 can be attributed to the error in the systems of measurement described earlier.

## 4.3 Results from International Firefighter Protective Clothing Breathability Research Project

Physiological results associated with the various garments were measured by and reported as part of the Breathability Research Project. Specifics of the testing involved are described in Chapter 2. Table 4.10 shows various physiological responses to each garment from the Mild Environment Protocol.

Table 4.10: Physiological Results from Mild Environment Protocol

| Garment | Initial $T_{sk}$* | Max $T_{sk}$ | Final $T_{sk}$ | Average $T_{sk}$ | Max Rise $T_{sk}$ | Final Rise $T_{sk}$ | Average Rise $T_{sk}$ |
|---|---|---|---|---|---|---|---|
| 1 | 32.326 | 35.588 | 34.397 | 34.726 | 3.262 | 2.071 | 2.400 |
| 2 | 32.744 | 35.648 | 34.544 | 34.929 | 2.904 | 1.800 | 2.185 |
| 3 | 32.562 | 35.897 | 34.954 | 35.053 | 3.335 | 2.392 | 2.491 |
| 4 | 32.652 | 36.063 | 35.336 | 35.253 | 3.412 | 2.684 | 2.602 |
| 5 | 32.532 | 35.788 | 34.450 | 34.911 | 3.256 | 1.918 | 2.379 |
| 6 | 33.107 | 35.859 | 34.660 | 35.075 | 2.753 | 1.553 | 1.968 |
| | Initial HR** | Max HR | Final HR | Average HR | Max Rise HR | Final Rise HR | Average Rise HR |
| 1 | 73.286 | 99.143 | 73.286 | 82.925 | 25.857 | 0.000 | 9.639 |
| 2 | 69.571 | 98.857 | 71.857 | 83.511 | 29.286 | 2.286 | 13.940 |
| 3 | 71.286 | 99.429 | 71.857 | 81.566 | 28.143 | 0.571 | 10.281 |
| 4 | 70.429 | 99.143 | 74.571 | 81.444 | 28.714 | 4.143 | 11.015 |
| 5 | 73.429 | 98.714 | 72.286 | 82.714 | 25.286 | -1.143 | 9.286 |
| 6 | 74.429 | 99.143 | 72.571 | 81.602 | 24.714 | -1.857 | 7.173 |
| | Initial $T_{core}$*** | Max $T_{core}$ | Final $T_{core}$ | Average $T_{core}$ | Max Rise $T_{core}$ | Final Rise $T_{core}$ | Average Rise $T_{core}$ |
| 1 | 36.820 | 37.286 | 37.160 | 37.101 | 0.466 | 0.340 | 0.281 |
| 2 | 36.931 | 37.331 | 37.226 | 37.146 | 0.400 | 0.294 | 0.215 |
| 3 | 36.837 | 37.200 | 37.071 | 37.037 | 0.363 | 0.234 | 0.199 |
| 4 | 36.749 | 37.266 | 37.131 | 37.038 | 0.517 | 0.383 | 0.290 |
| 5 | 36.834 | 37.291 | 37.040 | 37.071 | 0.457 | 0.206 | 0.237 |
| 6 | 36.869 | 37.206 | 37.037 | 37.035 | 0.337 | 0.169 | 0.166 |
| | Initial RH**** | Max RH | Final RH | Average RH | Max Rise RH | Final Rise RH | Average Rise RH |
| 1 | 58.133 | 88.617 | 86.933 | 77.331 | 30.483 | 28.800 | 19.197 |
| 2 | 62.780 | 86.700 | 86.700 | 79.342 | 23.920 | 23.920 | 16.562 |
| 3 | 68.560 | 94.443 | 94.443 | 82.308 | 25.883 | 25.883 | 13.748 |
| 4 | 64.800 | 97.257 | 96.986 | 87.230 | 32.457 | 32.186 | 22.430 |
| 5 | 63.080 | 91.300 | 90.860 | 78.864 | 28.220 | 27.780 | 15.784 |
| 6 | 64.200 | 95.450 | 95.083 | 81.206 | 31.250 | 30.883 | 17.006 |

* $T_{sk}$ = Skin Temperature **HR = Heart Rate
***$T_{core}$ = Core Temperature ****RH = Microclimate Humidity

Table 4.11 similarly shows the physiological responses to each garment from the Warm Environment Protocol.

**Table 4.11: Physiological Results from Warm Environment Protocol**

| Garment | Initial $T_{sk}$* | Max $T_{sk}$ | Final $T_{sk}$ | Average $T_{sk}$ | Max Rise $T_{sk}$ | Final Rise $T_{sk}$ | Average Rise $T_{sk}$ |
|---|---|---|---|---|---|---|---|
| 1 | 35.270 | 37.990 | 37.990 | 36.952 | 2.720 | 2.720 | 1.682 |
| 2 | 35.290 | 37.850 | 37.850 | 36.973 | 2.560 | 2.560 | 1.683 |
| 3 | 35.350 | 37.840 | 37.840 | 36.982 | 2.490 | 2.490 | 1.632 |
| 4 | 35.160 | 38.690 | 38.690 | 37.369 | 3.530 | 3.530 | 2.209 |
| 5 | 35.280 | 37.720 | 37.720 | 36.966 | 2.440 | 2.440 | 1.686 |
| 6 | 34.990 | 37.780 | 37.780 | 36.879 | 2.790 | 2.790 | 1.889 |
| | **Initial HR****| **Max HR** | **Final HR** | **Average HR** | **Max Rise HR** | **Final Rise HR** | **Average Rise HR** |
| 1 | 70.400 | 162.200 | 162.200 | 123.336 | 91.800 | 91.800 | 52.936 |
| 2 | 72.000 | 150.500 | 150.500 | 120.573 | 78.500 | 78.500 | 48.573 |
| 3 | 73.700 | 153.300 | 153.300 | 121.073 | 79.600 | 79.600 | 47.373 |
| 4 | 70.100 | 158.000 | 158.000 | 126.764 | 87.900 | 87.900 | 56.664 |
| 5 | 67.300 | 149.000 | 149.000 | 120.118 | 81.700 | 81.700 | 52.818 |
| 6 | 67.000 | 149.000 | 149.000 | 119.045 | 82.000 | 82.000 | 52.045 |
| | **Initial $T_{core}$*** | **Max $T_{core}$** | **Final $T_{core}$** | **Average $T_{core}$** | **Max Rise $T_{core}$** | **Final Rise $T_{core}$** | **Average Rise $T_{core}$** |
| 1 | 36.780 | 38.100 | 38.100 | 37.365 | 1.320 | 1.320 | 0.585 |
| 2 | 36.850 | 37.950 | 37.950 | 37.357 | 1.100 | 1.100 | 0.507 |
| 3 | 36.870 | 37.960 | 37.960 | 37.362 | 1.090 | 1.090 | 0.492 |
| 4 | 36.980 | 38.300 | 38.300 | 37.508 | 1.320 | 1.320 | 0.528 |
| 5 | 36.990 | 37.940 | 37.940 | 37.382 | 0.950 | 0.950 | 0.392 |
| 6 | 36.820 | 37.860 | 37.860 | 37.265 | 1.040 | 1.040 | 0.445 |
| | **Initial RH******| **Max RH** | **Final RH** | **Average RH** | **Max Rise RH** | **Final Rise RH** | **Average Rise RH** |
| 1 | 33.500 | 93.640 | 93.640 | 85.513 | 60.140 | 60.140 | 52.013 |
| 2 | 33.500 | 94.750 | 94.750 | 87.293 | 61.250 | 61.250 | 53.793 |
| 3 | 33.500 | 95.314 | 95.314 | 87.960 | 61.814 | 61.814 | 54.460 |
| 4 | 33.500 | 97.083 | 96.983 | 89.774 | 63.583 | 63.483 | 56.274 |
| 5 | 33.500 | 96.360 | 96.220 | 86.487 | 62.860 | 62.720 | 52.987 |
| 6 | 33.500 | 96.317 | 96.317 | 85.423 | 62.817 | 62.817 | 51.923 |

* $T_{sk}$ = Skin Temperature    **HR = Heart Rate
***$T_{core}$ = Core Temperature    ****RH = Microclimate Humidity

Physiological weight changes were also reported for each of the garments for the Breathability Research Project. Table 4.12 shows various weight changes for each garment from the Mild Environment Protocol.

**Table 4.12: Weight Changes from Mild Environment Protocol**

| Garment | Subject Weight Loss | | | Gear Weight Gain | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | Nude | In Station Uniform | In Gear | Turnout | Turnout Coat | Turnout Pants | Station Uniform | Underwear and Socks | Coat Liner |
| 1 | 0.530 | 0.427 | 0.316 | 0.054 | 0.034 | 0.019 | 0.030 | 0.047 | 0.016 |
| 2 | 0.511 | 0.409 | 0.327 | 0.053 | 0.033 | 0.023 | 0.131 | 0.036 | 0.019 |
| 3 | 0.460 | 0.467 | 0.271 | 0.061 | 0.034 | 0.029 | 0.036 | 0.040 | 0.023 |
| 4 | 0.500 | 0.450 | 0.177 | 0.150 | 0.079 | 0.074 | 0.076 | 0.076 | 0.070 |
| 5 | 0.433 | 0.373 | 0.289 | 0.046 | 0.030 | 0.016 | 0.017 | 0.026 | 0.011 |
| 6 | 0.483 | 0.347 | 0.294 | 0.077 | 0.053 | 0.024 | 0.043 | 0.047 | 0.026 |

Table 4.13 similarly shows the weight changes for each garment from the Warm Environment Protocol.

**Table 4.13: Weight Changes from Warm Environment Protocol**

| Garment | Subject Weight Loss | | | Gear Weight Gain | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | Nude | In Station Uniform | In Gear | Turnout | Turnout Coat | Turnout Pants | Station Uniform | Underwear and Socks | Coat Liner |
| 1 | 1.368 | 0.706 | 0.316 | 0.228 | 0.140 | 0.088 | 0.394 | 0.220 | 0.102 |
| 2 | 1.500 | 0.822 | 0.316 | 0.268 | 0.166 | 0.104 | 0.412 | 0.252 | 0.124 |
| 3 | 1.396 | 0.710 | 0.276 | 0.250 | 0.152 | 0.098 | 0.420 | 0.278 | 0.126 |
| 4 | 1.554 | 0.646 | 0.250 | 0.290 | 0.172 | 0.120 | 0.456 | 0.278 | 0.144 |
| 5 | 1.488 | 0.780 | 0.342 | 0.226 | 0.138 | 0.090 | 0.474 | 0.252 | 0.088 |
| 6 | 1.360 | 0.704 | 0.282 | 0.238 | 0.142 | 0.090 | 0.402 | 0.244 | 0.104 |

## 4.4 Discussion of Heat Transfer Data

Overall, the sweating manikin produced results more analogous to actual physiological responses than did the sweating hot plate. The only marked difference for any of the physiological results was attributed to wearing Garment 4 with no other significant differences reported between any of the other garments. Testing with the hot plate showed at least three distinct differences for thermal and evaporative resistances as well as total heat loss for either the standard or wear trial conditions. Testing with the manikin, however, showed no difference for thermal resistance and only two clear levels of evaporative resistance or total heat loss. Both the evaporative resistance and the predicted total heat loss for manikin clearly showed Garment 4 being remarkably different from all other garments where relatively minute differences were observed between ensembles. This result corresponds well with the physiological results and shows how the sweating manikin can be useful in making distinctions between garments that can be expected to manifest in a realistic wear trial.

### 4.4.1 Thermal and Evaporative Resistances

The hot plate and the manikin had some similar trends as well as some differences for both thermal and evaporative resistances of garments. Figures 4.1 and 4.2 show the thermal resistances of the various garments as measured by the hot plate and the manikin, respectively.

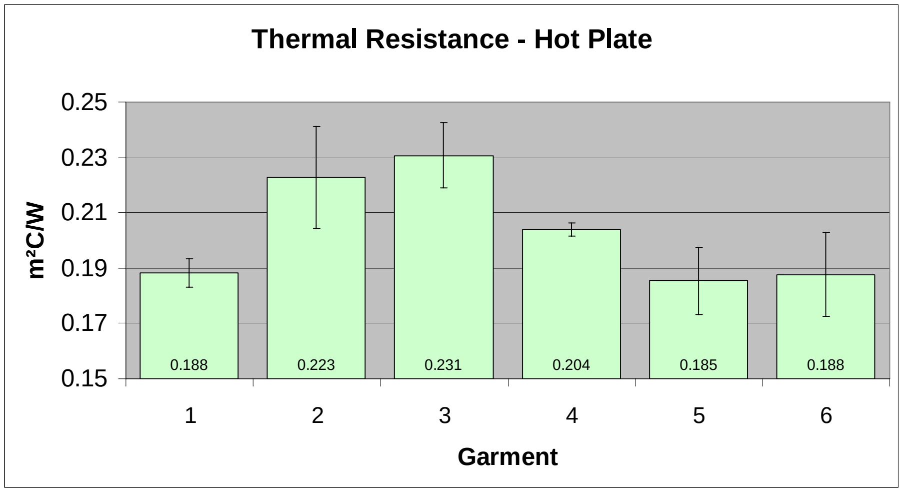



**Figure 4.1: Thermal Resistance ($R_{ct}$) Measured by the Hot Plate**

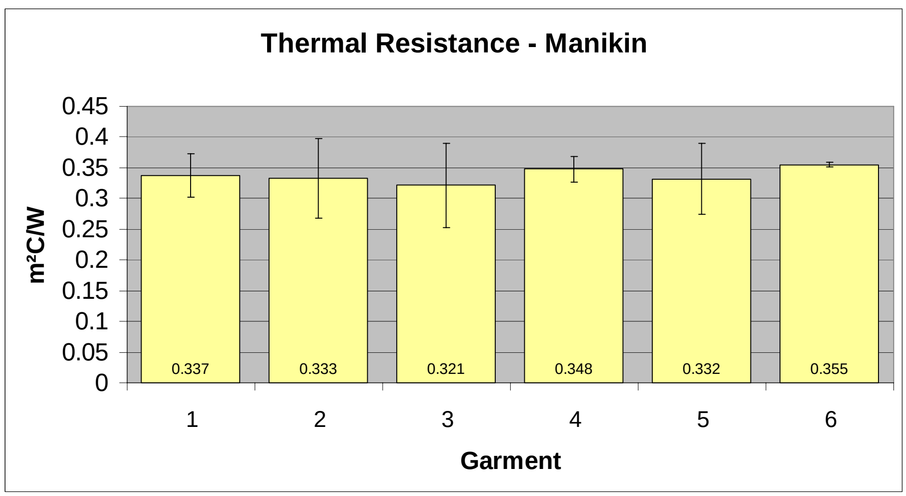



**Figure 4.2: Thermal Resistance ($R_t$) Measured by the Manikin**

The error bars on the graphs represent the upper and lower 95% confidence intervals determined by adding (subtracting) the standard error ($t_{\alpha/2,n-1} \cdot s/n^{½}$) to (from) the average values. Therefore, any error bars which overlap are not significant at the $\alpha = 0.05$ level (t-statistic p value) and any which do not are, likewise, significant at this level. Figure 4.1 shows that there are some obvious significant differences between the thermal resistances of the various material combinations measured on the hot plate. However, measured on the manikin there are no statistical differences in thermal resistance as can be seen in Figure 4.2. This result is likely due to the extra layers of clothing and particularly trapped air. It could also be due to the areas of the body which did not vary in how they were clothed (head, hands, and feet) and the parallel garment designs (same trim, pockets, etc.). The overall indication is that differences in thermal resistances up to about 20% on the hot plate may make little to no appreciable difference when worn in realistic situations.

The evaporative resistances don't show quite the same trends but do exhibit some similarities in the differences between values measured on the hot plate versus the manikin. Figures 4.3 and 4.4 show the evaporative resistances of the various garments as measured by the hot plate and the manikin, respectively.

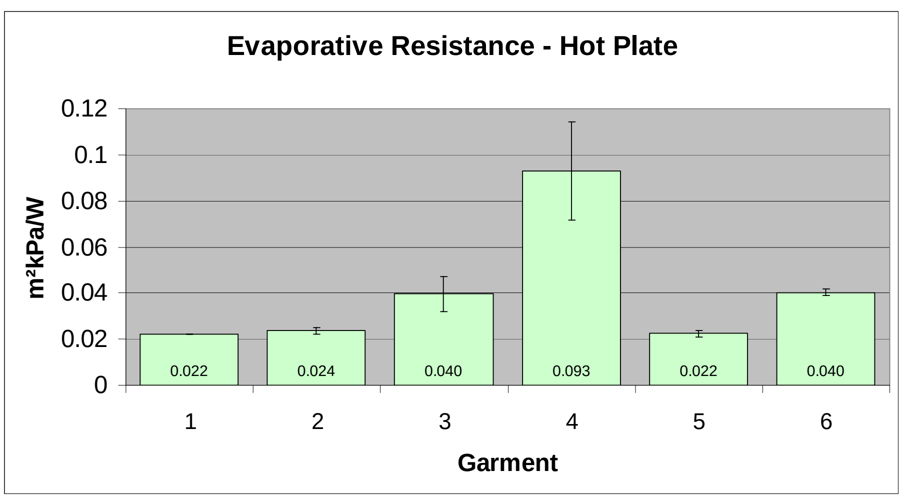



**Figure 4.3: Apparent Evaporative Resistance ($AR_{et}$) Measured by the Hot Plate**

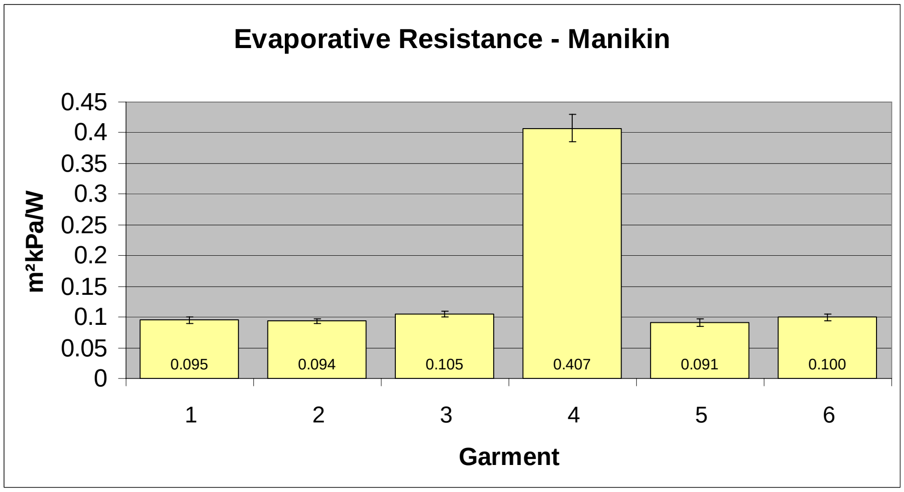



**Figure 4.4: Evaporative Resistance ($R_{et}$) Measured by the Manikin**

Figure 4.3 shows 3 distinct tiers of evaporative resistances measured on the hot plate corresponding to the 3 different moisture barriers used. However, these tiers are not so distinct when measured on the manikin. In fact, though Garments 3 and 6 are slightly higher than 1, 2, and 5 and small significant differences can associated with Garment 3 on the manikin when compared with some of the others, the overall differences between the all of breathable garments are rather minute. The evaporative resistance of Garment 4, however, remains on roughly the same order of magnitude above the breathable garments when measured on the manikin compared with the hot plate. The reasons for this phenomenon are uncertain, but it could be an indication that evaporative resistances of breathable garments may be affected more by trapped air or barrier substrates than the differences in the membranes themselves. This could explain why, like with the thermal resistances, the differences are much less pronounced. If the membranes themselves were fairly similar and the effect of air and fabric layers were then approximately equalized by the same reasons described for this effect on thermal resistance, then logic would support a similar effect on evaporative resistances amongst breathable garments. However, if the barrier technology were vastly different, as in the case of the non-breathable garment (4), the effect may be quite different. In this case, the area covered by the non-breathable garment may be the determinant factor. Since the water has no way to readily transfer through the material, it is likely that any evaporation taking place is finding some way around the material at interfaces or areas wear the non-breathable garment is not worn. Figure 4.5 shows the evaporative resistance of the various garments as measured by the manikin via Option 2 (amount of water evaporated).

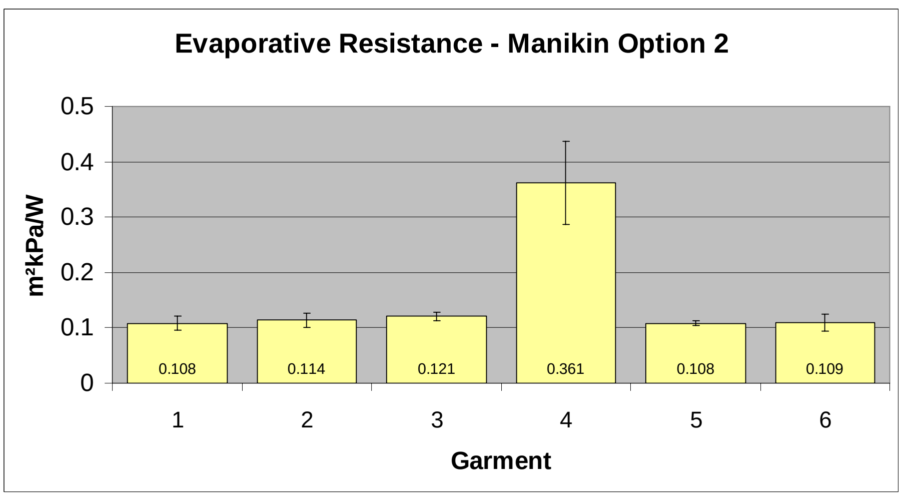



**Figure 4.5: Evaporative Resistance ($R_{et}$) Measured by the Manikin Using Option 2**

The numbers are slightly different due to errors in measurement and/or differences in the underlying theories of calculation, but the trends remain essentially the same giving them further validation.

### 4.4.2 Total Heat Loss

Thermal and evaporative resistances measured by the hot plate and manikin are intrinsic fabric (plus air layers) properties and thus not dependent on the ambient environment. Total Heat Loss, however, is dependent on the environment, but can be estimated for any environment based on the intrinsic thermal and evaporative resistances of the garments. For structural firefighter garments, the most common conditions for THL to be evaluated under are the standard test conditions called for in the ASTM F 1868 standard test method (25ºC, 65%RH). Figures 4.6 and 4.7 show the THLs of the various garments under standard conditions as measured by the hot plate and the manikin, respectively.

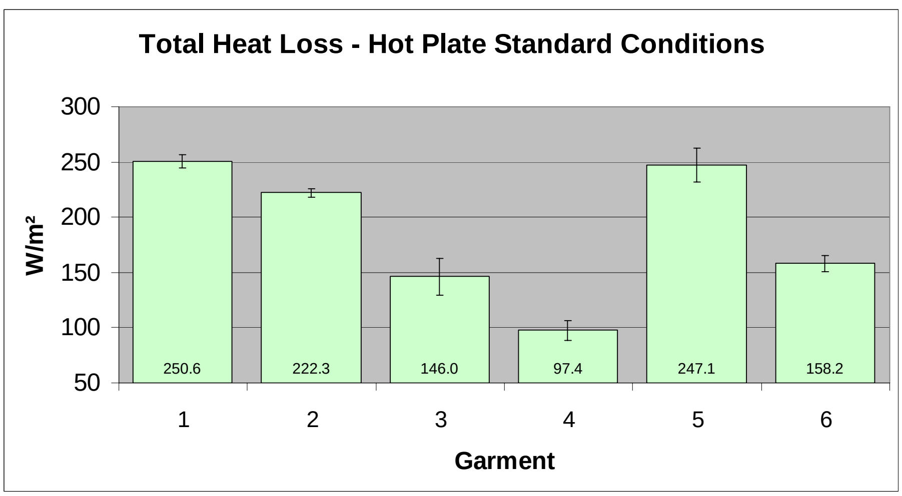



**Figure 4.6: Total Heat Loss Predicted by the Hot Plate for Standard Conditions**

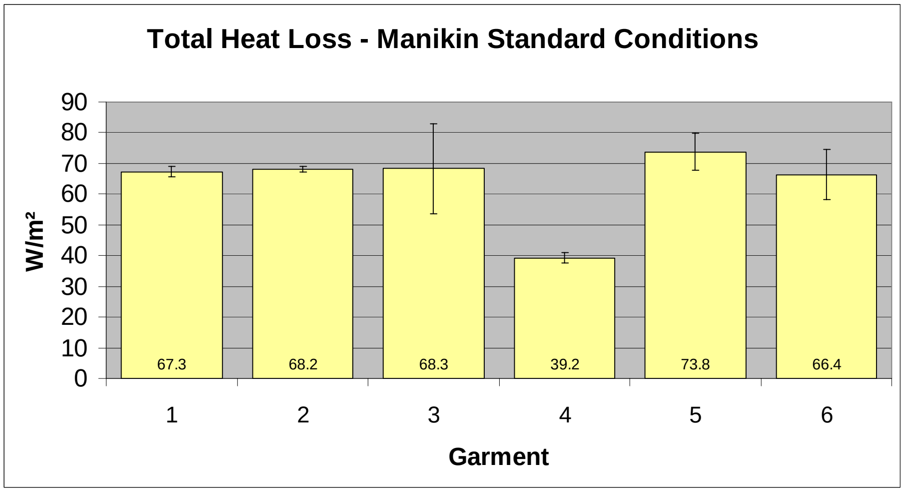



**Figure 4.7: Total Heat Loss Predicted by the Manikin for Standard Conditions**

Like the thermal and evaporative resistances, the THL values of the hot plate show many significant differences while those on the manikin show only a significant difference for Garment 4 versus the others. Thus, the manikin values are in agreement with the physiological findings whereas the hot plate value makes no clear distinction that can be linked with the physiological results. However, even though THL is usually only considered under the standard test conditions, when comparing values with physiological results, it would make sense that the actual heat loss be predicted for those conditions.

Figures 4.8 and 4.9 show the predicted THLs of the various garments modeled for the physiological conditions as calculated from the hot plate and the manikin data, respectively.

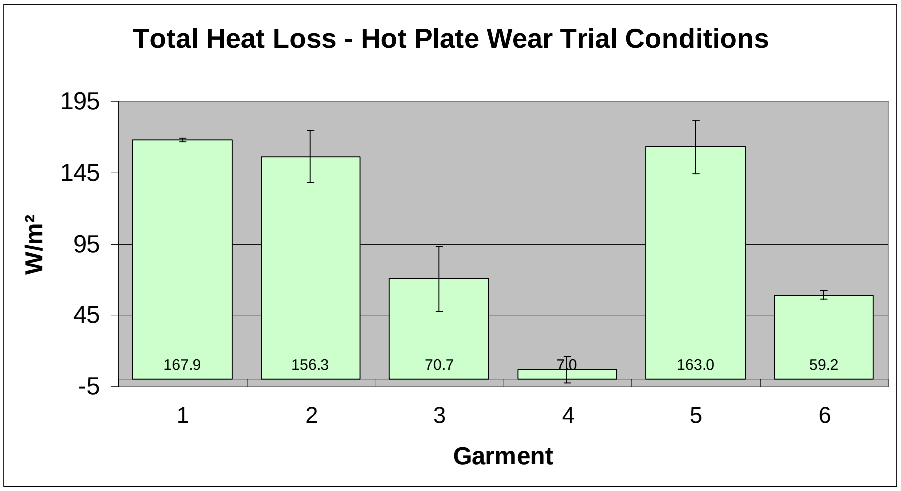



**Figure 4.8: Total Heat Loss Predicted by the Hot Plate for Warm Environment Conditions**

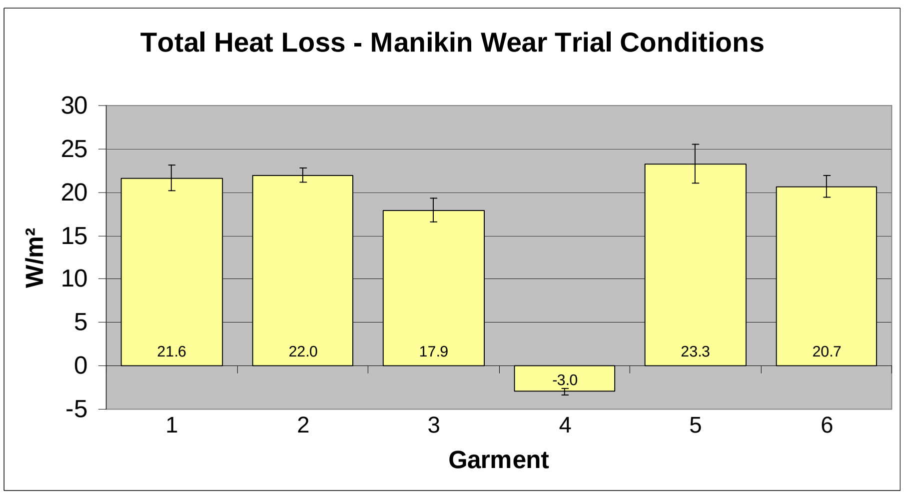



**Figure 4.9: Total Heat Loss Predicted by the Manikin for Warm Environment Conditions**

Figure 4.8 shows the same 3 distinct tiers of heat loss as were shown to be evident in the measurement of evaporative resistances on the hot plate. The most likely explanation for this is that under the conditions modeled no dry heat loss is possible. Because the conditions were modeled for 39ºC, some amount of heat gain would be expected.

However, with the skin set at 35ºC, the amount of heat gain would not be expected to be terribly great because of the relatively small temperature gradient. Therefore the evaporative resistance would be the dominant means of heat transfer. Figure 4.9 also shows similar trends as were seen in the manikin's thermal and evaporative resistances. Most of the breathable garments show no statistical differences from one another with the exception of Garment 3, which is statistically different but only slightly lower.

The results predict very low heat losses for all garments, but especially low for Garment 4 which actually shows that no heat loss is possible in the tested conditions. A slight heat gain is actually predicted due to the higher ambient temperature. Whether or not the amounts of actual heat loss possible would be this low is not known. Usually convection due to wind or body motion could aid slightly in heat loss. However, in these hot conditions convection due to wind or body motion would only be carrying warm air and could only be expected to facilitate in heat loss in that it may help carry away saturated air aiding in evaporation.

In order to more easily understand the balance between dry and evaporative heat loss, the total heat loss can be presented in a way in which it separates the two components. Figures 4.10, 4.11, 4.12, and 4.13 show the total heat loss values represented in Figures 4.6, 4.7, 4.8, and 4.9 broken up into their dry (C) and evaporative (E) components.

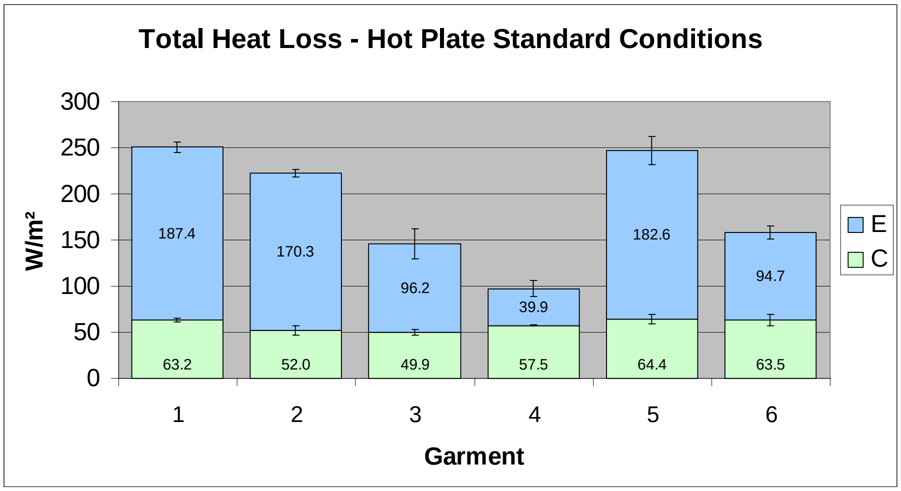



**Figure 4.10: Total Heat Loss Predicted by the Hot Plate for Standard Conditions divided the by Dry and Evaporative Components of Heat Loss**

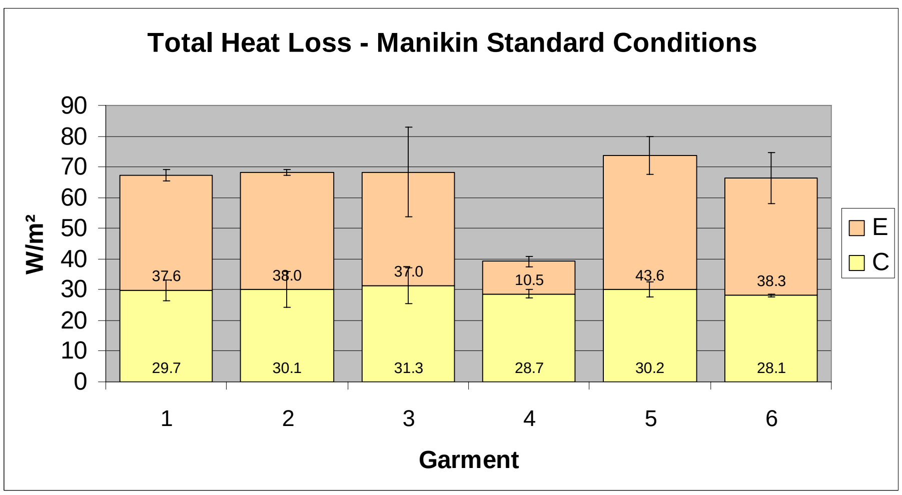



**Figure 4.11: Total Heat Loss Predicted by the Manikin for Standard Conditions divided the by Dry and Evaporative Components of Heat Loss**

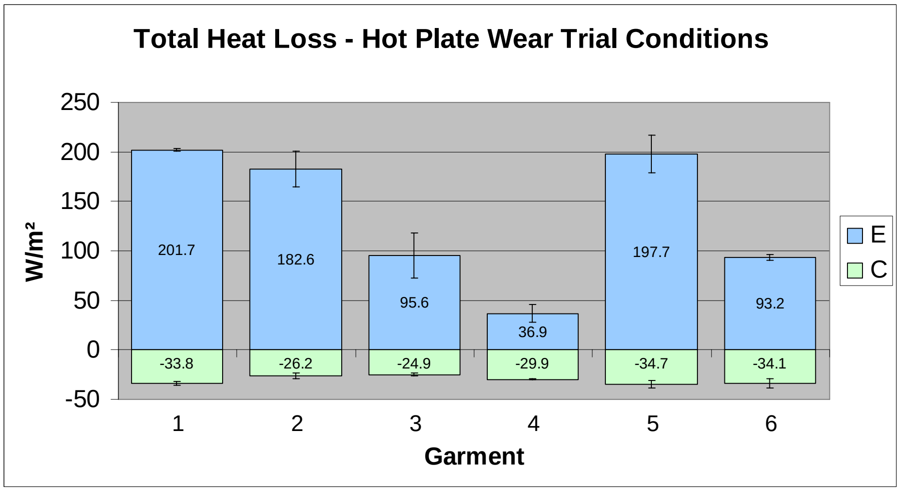



**Figure 4.12: Total Heat Loss Predicted by the Hot Plate for Warm Environment Conditions divided the by Dry and Evaporative Components of Heat Loss**

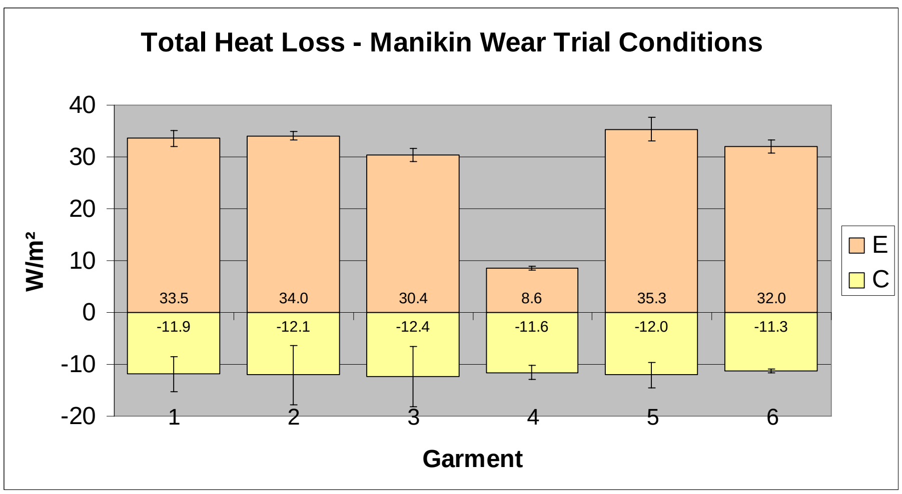



**Figure 4.13: Total Heat Loss Predicted by the Manikin for Warm Environment Conditions divided the by Dry and Evaporative Components of Heat Loss**

In each of the figures 4.10-4.13, the dry and evaporative components of heat loss add together to make up the total heat loss. In all of the figures, the dry components of heat loss appear to be much more similar to one another than the respective evaporative components. In either set of conditions, the hot plate seems to predict at least three different levels of evaporative heat loss corresponding to the different moisture barrier technologies, whereas the manikin seems to only make a substantial distinction between the breathable and non-breathable technologies.

### 4.5 Recovery During Rest: Discussion of the Predicted and Actual Range of Total Heat Loss

One observation reported by Stull (Field Evaluation of Protective Clothing Effects of Fire Fighter Physiology) was the ability of skin and core temperatures to recover during periods of rest. The indication is that during work, heat accumulates in the body since metabolic heat is produced at a greater rate than the body can dissipate through conduction, convection, radiation or evaporation. During rest, however, the metabolic heat production subsides enough that it can be overcome by the various mechanisms of heat loss and temperatures, thus, begin to recover. Skin temperature, as would be expected, responds quicker to work rate or environment than core temperature. This appears to be especially true for mild environments where the ambient temperature is much less than the skin temperature. If the human body were thought of as an inanimate object, the effect of the environment would first be realized at the surface and gradually heat the body according to the specific heat (heat capacity) of the object. However, since the human body produces heat, a more realistic depiction would be an inanimate object with an internal heater. This object can be either heated or cooled by its environment, but always must attempt to balance heat loss with the heat produced by this internal heating mechanism. In accordance with this analogy, the human body has a very complex internal system for heat regulation.  To keep from overheating, the body uses vasomotor control to dilate blood vessels in order to increase skin blood flow which raises skin temperature and increases heat transfer to the environment helping to regulate the core temperature [71].  Thus, the quicker response of skin temperature compared with the core can be attributed to sweating, surface heat exchange, and vasoregulation.

### 4.5.1 Recovery During Rest for Mild Environment Protocol

Though the human body is always producing heat, it produces it much more during work than during rest.  The recovery of skin and core temperatures during rest, as noted by Stull, indicates that during rest heat production occurs at a lesser rate than heat dissipation.  This ability to recover was also found for the Mild Environment Protocol of the International Firefighter Protective Clothing Breathability Research Project.  Figure 4.14 shows that even core temperature is able to recover at a considerable rate during these mild conditions [48].

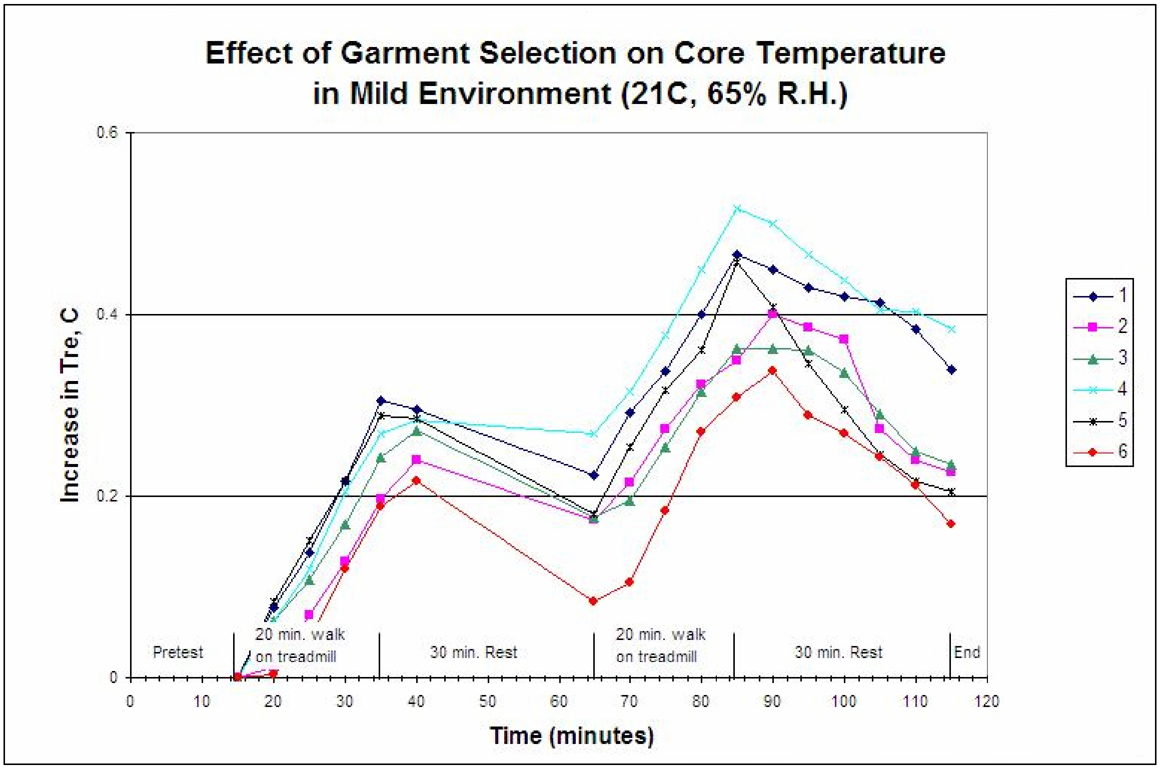



**Figure 4.14: Core Temperature Able to Recover During Periods of Rest for the Mild Environment Protocol**

The conditions here are fairly similar to the standard conditions where both the manikin and hot plate predict that heat loss is possible. The somewhat larger heat gradient, however, allows for moderately greater dry heat loss. Figure 4.15 shows the total heat loss predicted by the manikin for these conditions.

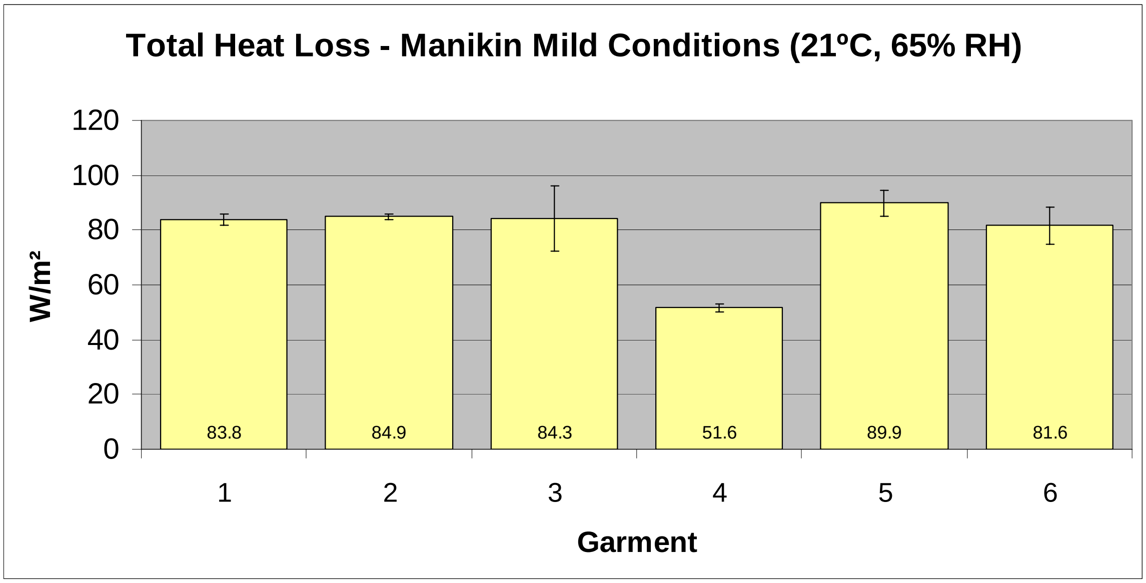



**Figure 4.15: Total Heat Loss Predicted by the Manikin for Mild Environment Conditions**

An average surface area of 2.19 $m^2$ was reported for the firefighters tested based on estimations from their heights and weights [48]. This means that the manikin would predict an average 113 W loss for the non-breathable system; breathable systems would show considerably greater heat loss. According to Goldman, a firefighter's body produces about 100 W while at rest [44]. Thus, during rest, the manikin would predict heat loss to be greater than heat production as is evident by the body's ability to recover during rest. Because firefighters also did not have any gear covering the hands or head during the Mild Environment Protocol, an even greater amount of heat loss would be expected than would be predicted by the manikin dressed in the full ensemble.

### 4.5.2 Recovery During Rest for Warm Environment Protocol

While a substantial amount of heat loss could be expected for the Mild Environment Protocol, the manikin predicted much less heat loss for the Warm Environment Protocol (Figure 4.9). For these conditions, the manikin predicted that no heat loss would be possible in the non-breathable garment (Garment 4) and that heat loss would be limited to about 51 W for even the most breathable garments. Considering an average heat production of 100 W while at rest, one would expect not to see any recovery during rest periods as indicated by the manikin. Figure 4.16 supports this notion, showing that no recovery was seen in any garment, even for skin temperature which responds more quickly than core temperature.

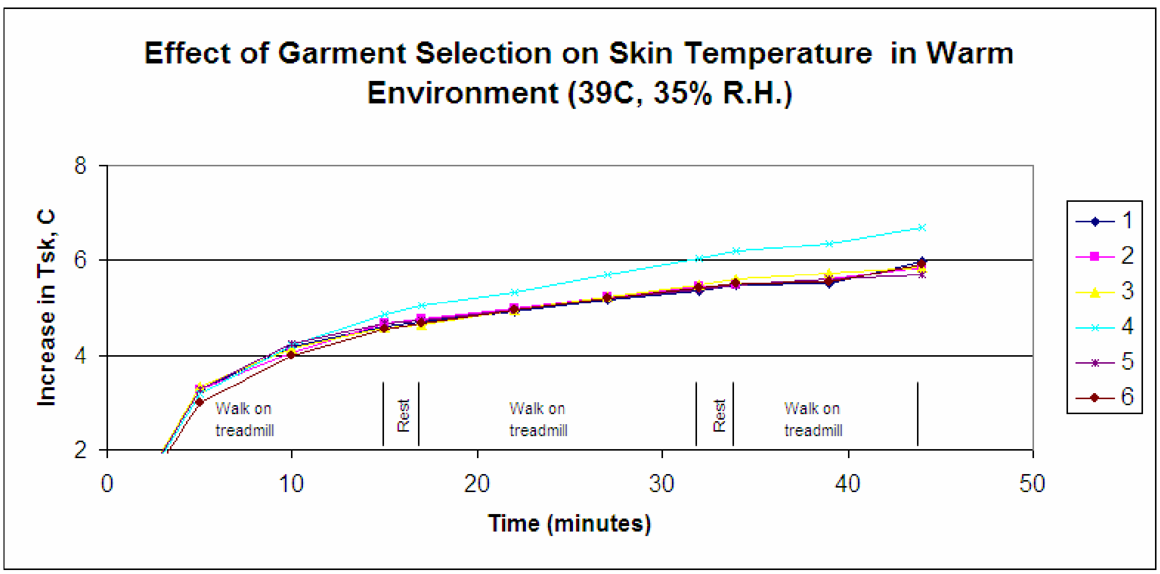



**Figure 4.16: Skin Temperature Unable to Recover During Periods of Rest for the Warm Environment Protocol**

Even though the hot plate would not predict recovery to be possible for Garment 4 under these conditions, it would predict recovery during rest to be possible for all other garments, which does not appear to be the case. Considering the average surface area of the firefighters, the heat loss predicted by the hot plate for these conditions would be well over the 100 W approximate heat production during rest for all breathable systems. This result suggests that the manikin is more in line with physiological responses in terms of actual amount of heat loss possible during realistic wear trials. It would be helpful to see how the trend of heat gain would continue for longer resting periods, but since the Warm Environment Protocol was not designed for this, one can only speculate that it would continue to rise (up to a certain point).

Another noteworthy result is that comparing the heat loss predicted for the Warm Environment conditions versus standard conditions, the Warm Environment conditions agree best with the observed heat gain. Using the standard conditions would predict that skin temperatures could recover during rest for all five breathable garments given the estimated heat production. The implication is that, although differences between garments are similar whether modeled for the standard or the actual conditions, the actual amount of heat loss is better predicted by modeling for the actual conditions. Although this result may seem obvious, oftentimes THL is only measured and discussed under the standard conditions. In general, when discussing heat loss, it may be best to speak in terms of total heat loss for the standard conditions since that is the usual way of describing heat loss in a generic environment. However, if the relevant environmental conditions are known, it makes sense to model heat loss for those conditions in order to achieve the most relevant results.

### 4.6 Correlations Between Hot Plate Values and Physiological Response

Stull demonstrated that correlations could be derived that could relate material properties to physiological responses. Particularly, he was able to show a strong correlation between sweating hot plate values and rise in core temperature. No such correlations, however, were found between values related to the hot plate THL and any difference in core temperatures for either the Mild Environment or Warm Environment Protocol of the Breathability Research Project.

#### 4.6.1 Discussion of Differences in Field Evaluation Results and Breathability Research Project Results

There are several reasons that could explain why such correlations were found for one project and not the other. Particularly, the conditions, materials, and protocols were all significantly different. These differences are very likely responsible for the differences in the findings.

##### 4.6.1.1 Differences in Test Conditions

Some of the conditions for the various testing protocols were quite different. The Warm Environment Protocol of the Breathability Research Project was much hotter and much less humid than any of the other protocols. Any heat loss would be expected to be entirely owed to evaporation. The Mild Environment Protocol conditions were much more similar to the conditions of both protocols of the Field Evaluation of Protective Clothing Effects of Fire Fighter Physiology. These conditions were much closer to the standard hot plate conditions under which the THL values had been measured. Consequently, THL values could be expected to be better predictions for these conditions where dry and evaporative heat losses contribute more evenly to the total heat loss. Here the differences in the results between the Mild Environment Protocol of the Breathability Research Project and either protocol of the Field Evaluation could be more attributed to differences in the material evaluated, the clothing configuration, and the work protocol.

#### 4.6.1.2 Differences in Garments Evaluated

The garments evaluated are likely to have had a significant impact on the findings. The Field Evaluation evaluated 3 non-breathable systems (2 non-compliant with NFPA 1971 standard), 3 systems spread along the range of the typical compliant, breathable systems, and 1 'extremely breathable' system (non-compliant with NFPA 1971 standard). The Breathability Research Project evaluated 1 non-breathable system and 5 breathable systems (all compliant with NFPA 1971 standard) with THL values within the typical range for firefighter garments available at the time. The garment selections resulted in much different ranges for the resistances and THL values for the Field Evaluation than for the Breathability Research Project as characterized by the boxplots in Figures 4.17-4.19.

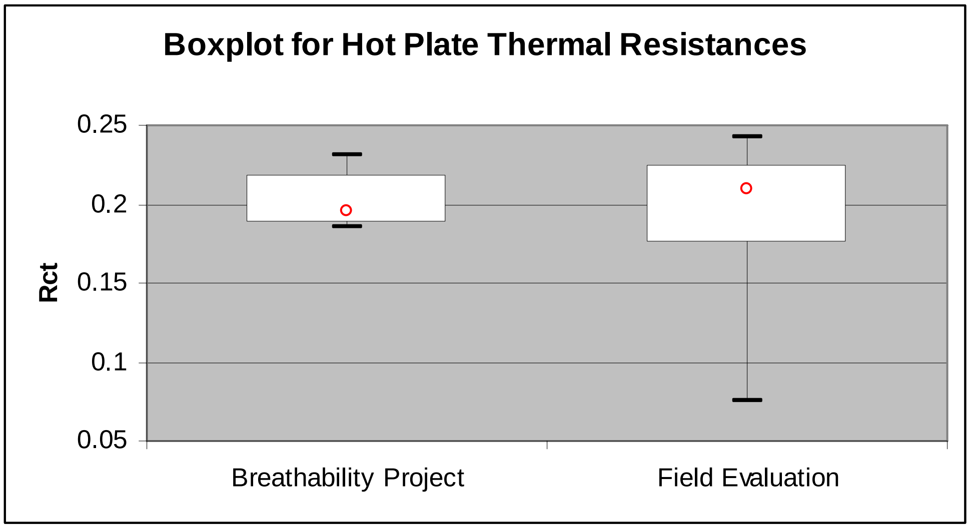



**Figure 4.17: Boxplot for the Thermal Resistances of Garments Used for the 'International Research Breathability Research Project' and 'Field Evaluation of Protective Clothing Effects on Fire Fighter Physiology'**

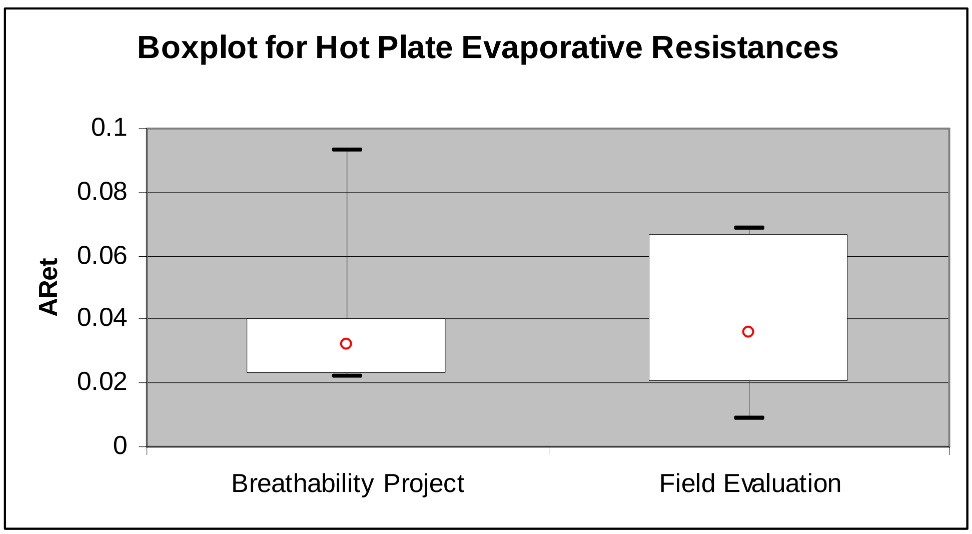



**Figure 4.18: Boxplot for the Evaporative Resistances of Garments Used for the 'International Research Breathability Research Project' and 'Field Evaluation of Protective Clothing Effects on Fire Fighter Physiology'**

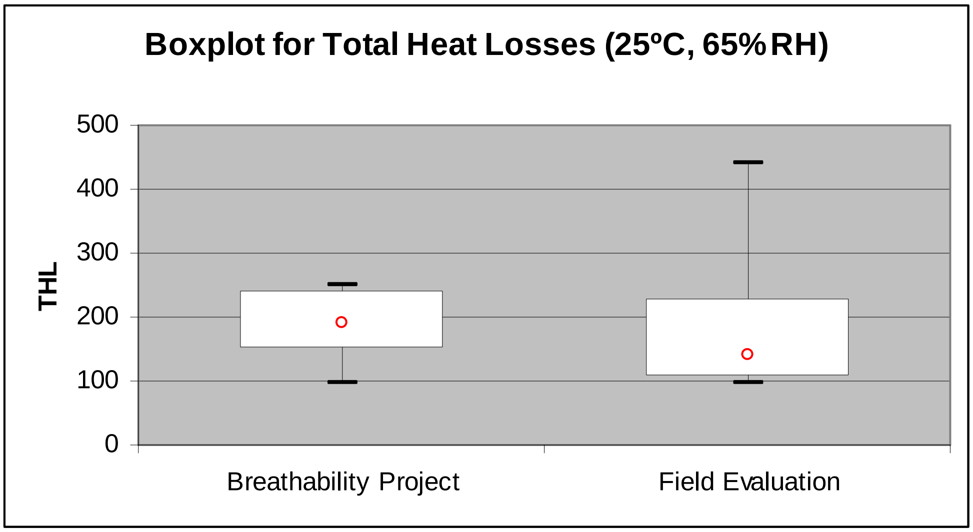



**Figure 4.19: Boxplot for the Total Heat Losses (Standard Conditions) of Garments Used for the 'International Research Breathability Research Project' and 'Field Evaluation of Protective Clothing Effects on Fire Fighter Physiology'**

The differences in the ranges for the values is worthy of consideration. Comparing the Field Evaluation to the Breathability Research Project, the range for thermal resistance is over 3 times greater and the range for total heat loss is more than twice as great. However, the range for evaporative resistance is actually less for the Field Evaluation. An interesting observation, though, is that despite the differences in the ranges for thermal and evaporative resistances, the rank order for THL (highest to lowest) is nearly identical to the rank order for evaporative resistance (lowest to highest) for both sets of garments. The significance of this is open to interpretation but could be an indication that the differences in THL are achieved mostly through differences in evaporative resistance.

Manikin testing showed that differences in thermal resistances measured on the hot plate could no longer be realized, once the additional clothing and air layers were accounted for, on the manikin. This was at least the case for the Breathability Research Project; it is unknown how much the difference in thermal resistances may be mitigated for the Field Evaluation where the range of thermal resistances was over three times as great. The greater range of thermal resistances could lead to an increased dependence of the THL on the dry component of heat loss.

THL is dependent on conditions, but also the materials. Two garments could have equal THL values, but have very different thermal or evaporative resistances. For example, a garment with have a very low evaporative resistance but a very high thermal resistance could have the same THL value as a garment with a moderately high evaporative resistance and low thermal resistance in the right conditions. However, once the conditions were changed, the THL values could become very different from one another. Thus, the differences in materials could be another contributing factor to the differences in results between the trials.

#### 4.6.1.3 Differences in Testing Protocol

Other contributing factors could be owed to the protocol. The clothing configuration for the Mild Environment Protocol for the Breathability Research Project was quite different from any of the other protocols. The fact that the firefighters didn't wear any gloves or head gear for this protocol could have a considerable impact on the heat transfer. Increased ventilation and unrestricted evaporation (where skin was exposed) would undoubtedly reduce heat stress which would in turn diminish physiological responses. Differences in work rates between garments would also affect the physiological response.  Work rates that are set too high or too low could cloud the results since it would be harder to recognize differences between garments.

#### 4.6.1.4 Summary of Differences

It is interesting that in the Field Evaluation such a strong relationship was found between THL and core temperature.  Logically, the wider range would help to discern the relationship between THL and core temperature response since differences between garments would be exaggerated, better overcoming inter-individual differences. Interestingly though, the relationship appears stable; even if the most extreme points were to be eliminated, the slope would only be changed slightly.  One might expect since this relationship appeared strong and rather stable along an extensive range that a very similar trend would emerge for a separate trial.  However, likely due to the conditions, materials, clothing conditions, and/or exercise protocols (as described above), there was no evidence apparent in either protocol for the Breathability Research Project that such a trend existed.  In fact, it did not; even if THLs were adjusted for the appropriate conditions or core temperature rises were modeled at different times, the relationship could not be forged.  This is largely due to the fact that there were no significant differences between physiological responses to the five breathable garments.  Much of the differences within the range of responses for the breathable garments, therefore, could be expected to be due to random variation.

#### 4.6.2 Inverse Hyperbolic Relationship Between THL and Core Temperature Response

During testing, the manikin was dressed according to the Warm Environment Protocol, in part, to assess whether or not it could offer any additional help in explaining why no clear relationship between THL (1/THL) and core temperature (rise) existed as it had in the Field Evaluation. Figure 4.20 shows the correlation between the rise in core temperature and 1/THL found for the Ladder Company Simulation.

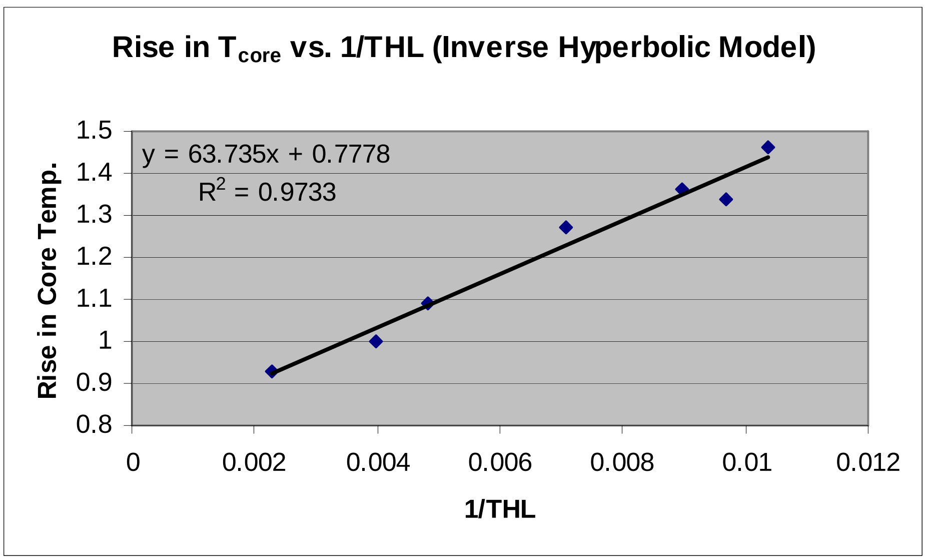



**Figure 4.20: Correlation between 1/THL and Core Temperature Response found for the 'Field Evaluation of Protective Clothing Effects on Fire Fighter Physiology' (Ladder Company Simulation Results are shown in this Figure)**

The linear relationship in Figure 4.20 is indicative of the inverse hyperbolic relationship between core temperature rise and THL. There are no obvious problems with the relationship that would cast doubt on its validity. This relationship, however, was not found for either protocol of the Breathability Research project.  Figures 4.21 and 4.22 show the max rise in core temperature versus 1/THL for each of the protocols.

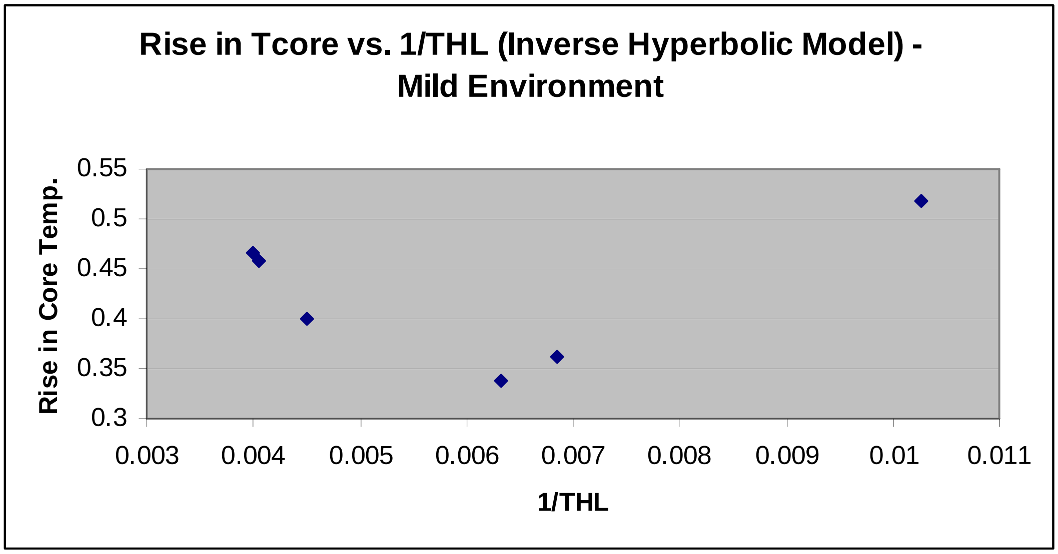



**Figure 4.21: No Significant Correlation between 1/THL and Core Temperature Response was found for the Mild Environment Protocol of the 'International Breathability Research Project'**

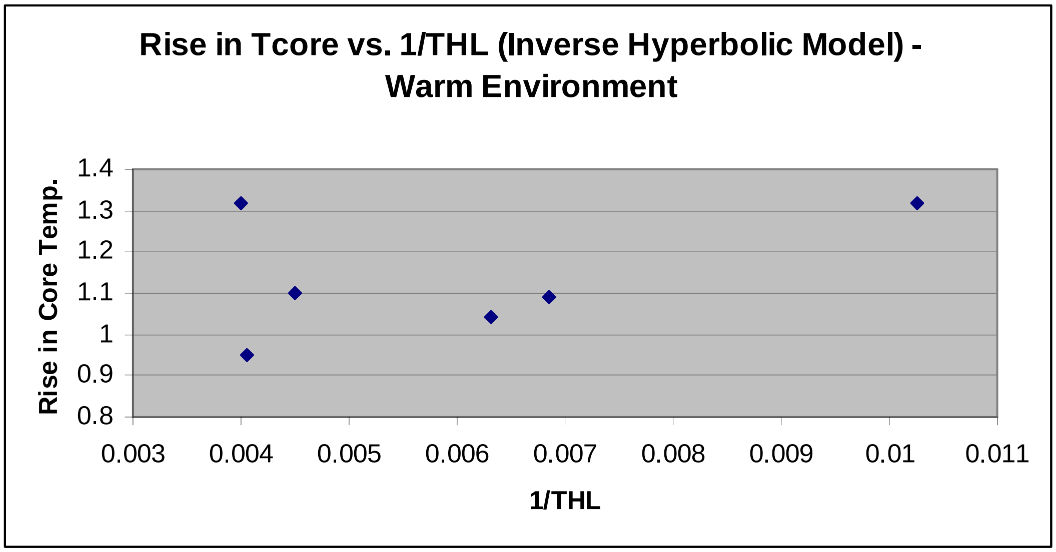



**Figure 4.22: No Significant Correlation between 1/THL and Core Temperature Response was found for the Warm Environment Protocol of the 'International Breathability Research Project'**

There is no clear evidence of any relationship tying the rise in core temperature to 1/THL. That is not to say that there is not some sort of relationship, but the results of this study show no evidence of such a relationship. In fact, in the Breathability Research Project, only Garment 4 induced significantly different physiological responses. None of the other 5 garments could even be decisively differentiated in terms of the physiological responses they invoked.

Referring back to Figures 4.6 and 4.7 gives a basis for a very conceivable explanation for why the hot plate could not be correlated with core temperature. Differences in total heat losses on the hot plate could not be recognized on the manikin except in the case of Garment 4. The additional clothing and air layers are likely the reason that heat losses became indistinguishable from one another. Therefore, the manikin offers evidence that even though hot plate values differed, these differences could not be appreciated in garment form. Correlations, therefore, could not be expected, especially with the additional variability of individual responses to heat stressors. The fact that a correlation was found for the Field Study may have to do with differences in the range of resistances of the materials as suggested earlier. The sweating manikin could be a helpful tool in determining how material differences (resistances) manifested on the garment level. If the manikin were to reveal that heat losses on the manikin were more readily discernible from one another, it could be an indication that physiological results may also be more readily discernible from one another.

### 4.7 Correlations Between Hot Plate and Manikin Values

In the past, correlations have been reported between hot plate and manikin values when similar garment designs wore worn. However, these correlations were not found for this study. At least, there was little evidence of the expected linear relationships that was found to relate hot plate and manikin resistances or heat losses.

#### 4.7.1 Thermal and Evaporative Resistance Correlations

Figures 4.23 and 4.24 show the thermal and evaporative resistances for the manikin versus the hot plate.

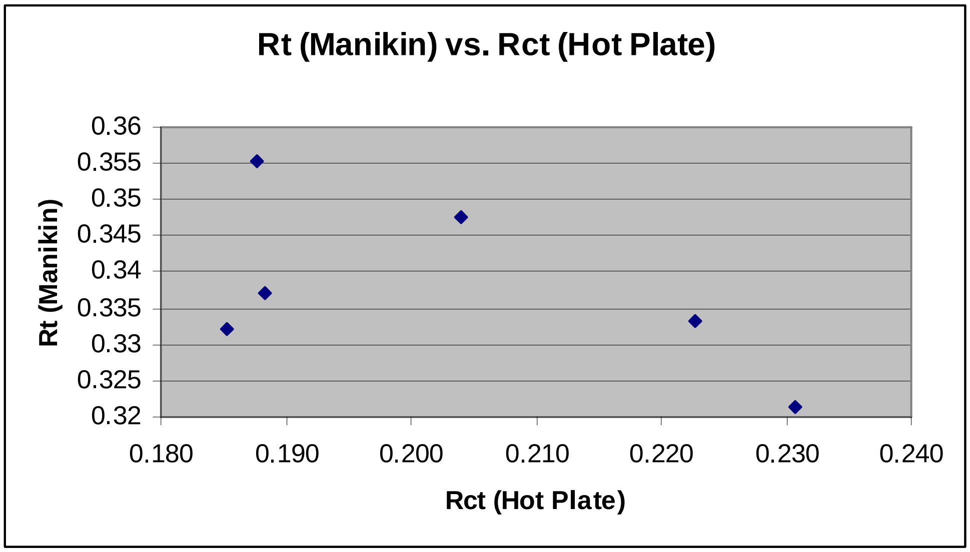



**Figure 4.23: No Significant Correlation between the Thermal Resistance Measured by the Hot Plate and Thermal Resistance Measured by the Manikin**

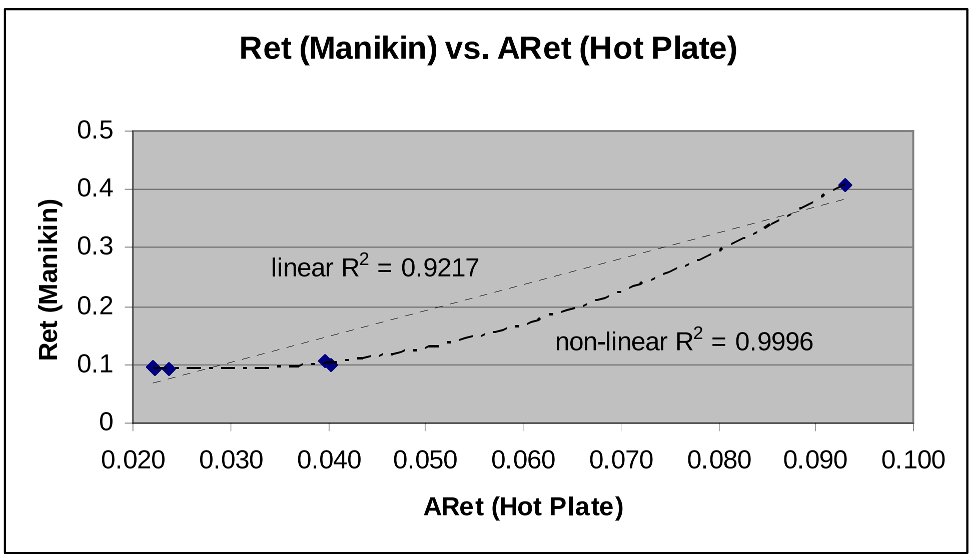



**Figure 4.24: Relationship between the Evaporative Resistance Measured by the Hot Plate and the Evaporative Resistance Measured by the Manikin is likely to be Non-linear in Nature**

The lack of any clear relationship for the thermal resistances can be attributed to the fact that the manikin values were not significantly different from one another. Since none of the values were significantly different from one another, it would be impossible to define a meaningful relationship based on these thermal resistance values. For the evaporative resistance, on the other hand, there does seem be some sort of relationship between the hot plate and manikin values. A linear relationship has an $R^2$ value of 92.2% which is a rather strong correlation. However, the leverage of Garment 4 in this case is likely responsible for the strength of the correlation (leverage discussed in Appendix). Examining the graph, it appears as if a non-linear relationship may be more appropriate. The lack of observations along the central portion of the overall range for the evaporative resistance, however, makes it difficult to assess what shape the non-linear relationship might take. A 2$^{nd}$ order polynomial relationship as is depicted in Figure 4.24 would not be unreasonable.

In order to make sense of this relationship, one must consider the moisture barrier's role in resistance to evaporation in comparison with all of the other layers. In hot plate testing, air layers are minimal and resistances are more owed to fabric properties. Thus, without a fully developed boundary air layer between each layer of the composite, the contribution of each fabric layer is accentuated. In this situation, the evaporative resistance would be expected to be most dependent on the rate at which water could diffuse through the moisture barrier. When on the manikin, however, the boundary air layers become more fully developed and additional layers of clothing and air are present throughout most of the body. The result of the additional layers is that evaporative resistance should be less dependent, relatively, on the ability to diffuse through the moisture barrier and more equally dependent on the rate at which moisture can transfer through all of the additional air and fabric layers.  So long as moisture could diffuse through the moisture barrier at a rate similar to which it was arriving at the moisture barrier (i.e. evaporating through air layer, station uniform, air layer, thermal liner, air layer), then evaporative resistance may be only slightly different for two garments where the differences were more accentuated on the hot plate.  However, if a moisture barrier has very low or no breathability, then one would expect that it would become, by far, the limiting factor for evaporation.  This would cause the evaporative resistance to be most dependent, similar to hot plate testing, on the rate at which moisture could diffuse through the moisture barrier.  Thus, as breathability of the moisture barrier fell below a certain point, the slope of the relationship between hot plate and manikin evaporative resistances could be expected to quickly change.  This notion is supported by the fact that the apparent slope at the lower extreme of evaporative resistance (manikin) is much different than the slope connecting the higher extreme to any other measured points.  However, more testing along the central portion of the range would be needed in order to confirm and better define such a relationship between hot plate evaporative resistances and evaporative resistances for clothing worn in a realistic fashion.

### 4.7.2 Total Heat Loss Correlations

Because none of the thermal resistances measured on the manikin were significantly different from one another, differences in total heat loss measured on the manikin were based almost entirely on the differences in evaporative resistance.  Figure

4.25 shows the total heat loss (standard conditions) related to the evaporative heat loss (standard conditions).

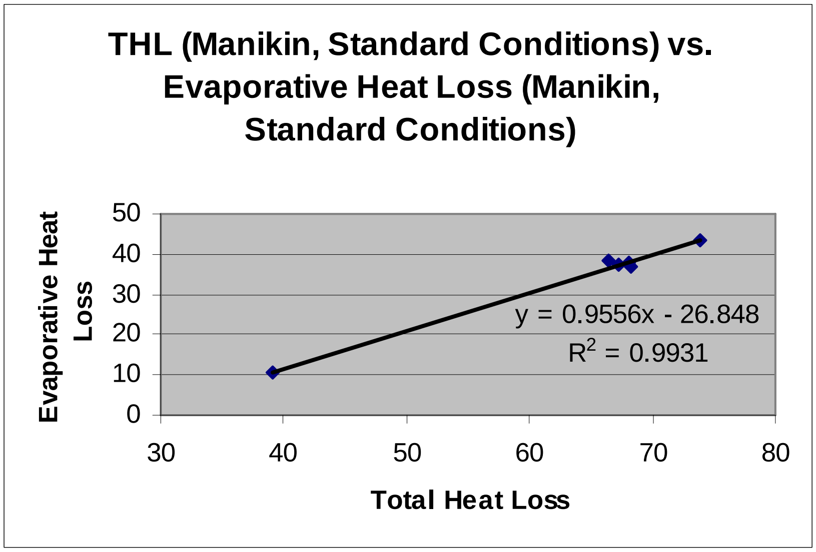



**Figure 4.25: Relationship between Total Heat Loss and Evaporative Heat Loss on the Manikin shows a Near Complete Dependence**

In standard conditions the dry component of heat loss contributes 29.7 ± 1.6 W/m² to the total heat loss regardless of the garment worn (Table 4.4). Thus, the difference in total heat loss for each garment is due to the difference in evaporative heat loss as shown in Figure 4.25. If each garment had a dry heat loss of exactly 29.7 W/m², the resulting equation would have a slope of 1 and an intercept of -29.7. The difference between these hypothetical values and the slope and intercept of the regression line shown in Figure 4.25 is actually quite small. In fact, using the equation $y = 1x – 29.7$ would still give an $R^2$ value above 99%.

The implication of these finding is that the differences in THLs between the garments were based almost completely on the garments' ability to lose heat through evaporation (for the garments tested). Even for standard conditions, which are fairly mild, differences between garments in terms of dry heat loss are insignificant. Furthermore, differences in evaporative resistances that were rather sizeable on the hot plate (~76%) were severely diminished on the manikin (~10%) except in the case of the non-breathable garment. On the hot plate there were three distinct levels of breathability (evaporative resistance) observed for the composites measured. The composite with the lowest breathability (the non-breathable Garment 4) had an evaporative resistance 310% greater (on average) than the three garments identified as having the highest level of breathability (Garments 1, 2 and 5) as measured by the sweating hot plate. Similar results were found for the manikin where Garment 4's evaporative resistance was found to be 337% greater than the average for the same three garments.

The manikin is very valuable, in this way, for understanding why only Garment 4 provoked physiological differences during the wear trial. The hot plate showed distinct differences between garments for both thermal and evaporative resistances as well as THL values. However, the manikin showed that thermal resistances could not be differentiated when the garment was dressed as it would be worn. In addition, evaporative resistances, which were present in three different, distinct levels on the hot plate, were affected in a way in which only two truly distinct levels remained recognizable. Although some statistical differences could be acknowledged to separate two lower levels, the difference between them was reduced so dramatically that they were no longer clearly exclusive. The result was that the total heat loss measured on the manikin, mostly determined by the evaporative resistance, was quite comparable for the five breathable garments and only appreciably different for the non-breathable Garment 4. The results of the manikin testing are in good agreement with the physiological results from the Warm Environment Protocol of the Breathability Research Protocol. This is important for the validation of the capability and usefulness of the manikin as a supplemental tool in predicting heat stress.

Since the total heat loss was linked so strongly to the evaporative heat loss, one may expect that total heat losses would also show evidence of a non-linear relationship between values measured on the hot plate and values measured on the manikin. Figures 4.26 and 4.27 show possible linear and non-linear relationships relating the heat loss values for standard conditions and Warm Environment Protocol conditions, respectively.

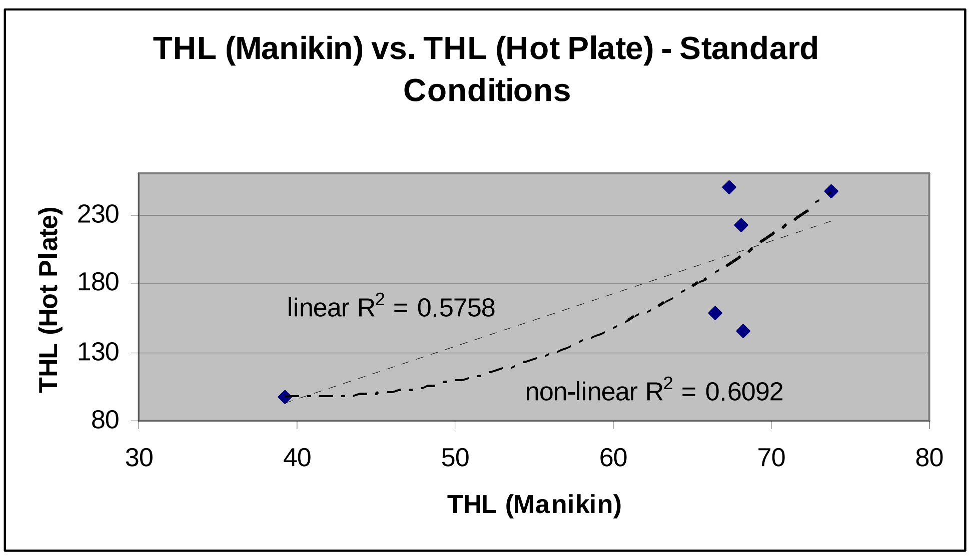



**Figure 4.26: Possible Linear or Non-Linear Relationships between Total Heat Loss Predicted by the Manikin and Total Heat Loss Predicted by the Hot Plate for Standard Conditions**

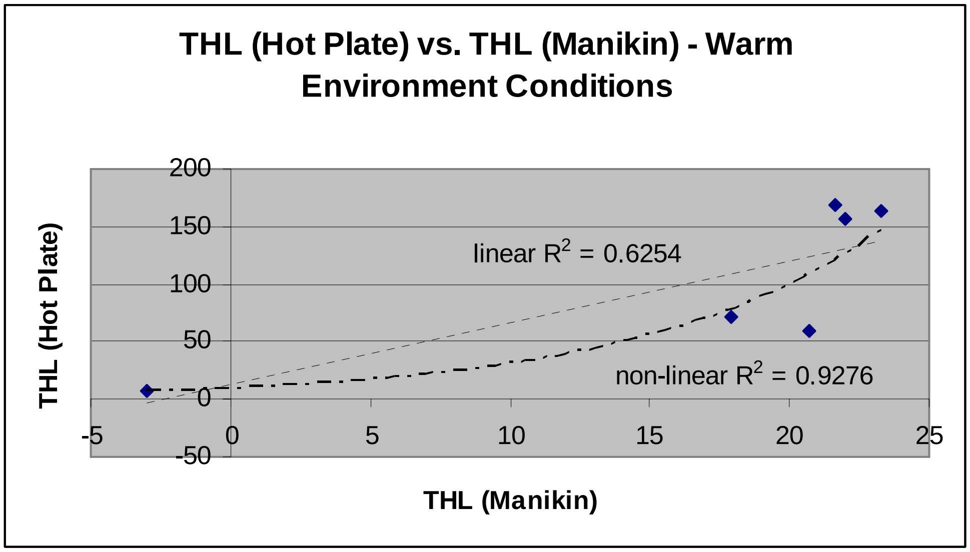



**Figure 4.27: Possible Linear or Non-Linear Relationships between Total Heat Loss Predicted by the Manikin and Total Heat Loss Predicted by the Hot Plate for Warm Environment Conditions**

Though neither relationship is exceptionally strong for the standard conditions, the non-linear relationship is somewhat stronger. This is also true for the Warm Environment Protocol conditions except that the relationships are stronger overall for these conditions. The reason that the relationships are stronger for the Warm Environment Conditions is that the total heat loss is much less dependent on the dry heat loss in these conditions, since the temperature gradient is much less and the humidity gradient is substantially greater. The greater dependence on evaporative heat transfer means that the relationship between hot plate and manikin evaporative resistances is more accentuated and the differences (or error) associated with dry heat loss play less of a role. Besides the stronger $R^2$ values for the non-linear relationships, they are also more visually appealing.

It is easier to imagine the trends continuing along the curvilinear relationships than to make them out as random error components of a linear relationship.

Although these non-linear relationships for THL are appealing, it would be unsound to claim that they could be expected to be repeatable for other trials based solely on the findings from this trial. The evidence suggests that the nature of the relationship between hot plate and manikin THLs for this testing can be traced back to the relationship between their evaporative resistances. Therefore, because differences in thermal resistances appear to have played little part in overall differences in heat loss, it is difficult to assess how the relationship might be changed if differences in thermal resistances could be realized on the garment level.

### 4.8 Correlations Between Manikin Values and Physiological Response

Although, relationships between hot plate and manikin heat transfer properties are reasonable based on the results of this trial, there is little prospect that a valid relationship could be well-defined that would relate any of these heat transfer properties to physiological responses. This is due to the fact that, as mentioned earlier, there were no significant differences in physiological responses for any of the 5 breathable garments. The result is that for most relationships based on any of the physiological responses there is a semi-random conglomerate of five points (garment averages) for the group of breathable garments and just one substantially different result related to the non-breathable garment. Relationships can still be defined, but their meanings may be limited for statistical reasons as discussed in Appendix.

Because core temperatures responded slower and significant differences were unable to sufficiently develop, skin temperature response was instead examined as a physiological indication of heat stress. Also, because subjects in Garment 4 were only able to consistently complete 44 minutes of work, this was used as the end point of the experiment for making equal comparisons between garments. The skin temperatures were always at their maximum point at this mark since this was at the end of a work period while skin temperatures were continuing to rise and any ensuing data (for subjects who continued to work beyond 44 minutes) was not taken into consideration. A good correlation was found between the peak rise in skin temperature and the THL on the manikin as shown in Figure 4.28.

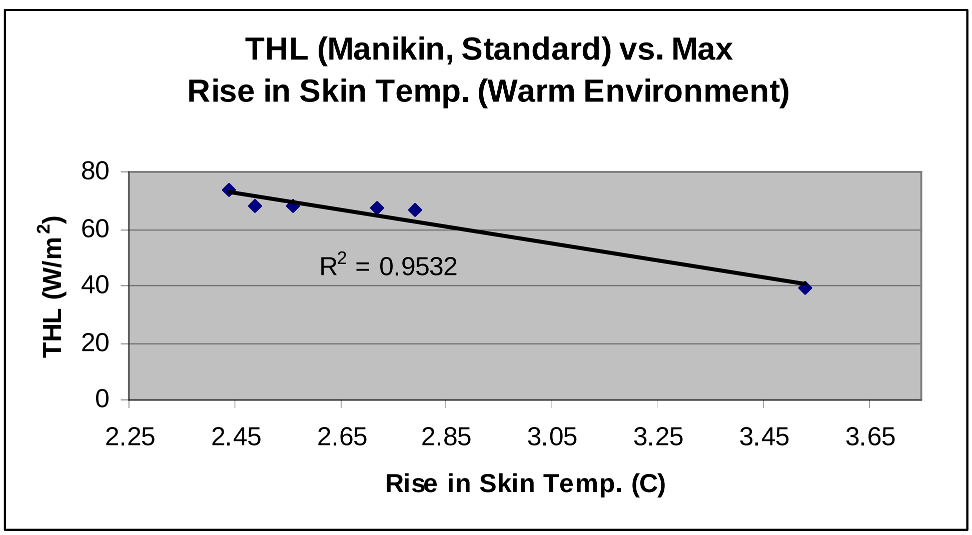



**Figure 4.28: Good Correlation between Skin Temperature Response for the Warm Environment Protocol and Total Heat Loss Predicted by the Manikin (Standard Conditions)**

Although the correlation is fairly strong, it is considerably influenced by Garment 4. There were little to no significant differences between any of the other points for either heat loss or rise in skin temperature. Still, the small differences in a way correspond with one another since where there was little difference between THL values, there was likewise little difference in skin temperature response. The same is not exactly true of hot plate THL values as shown in Figure 4.29.

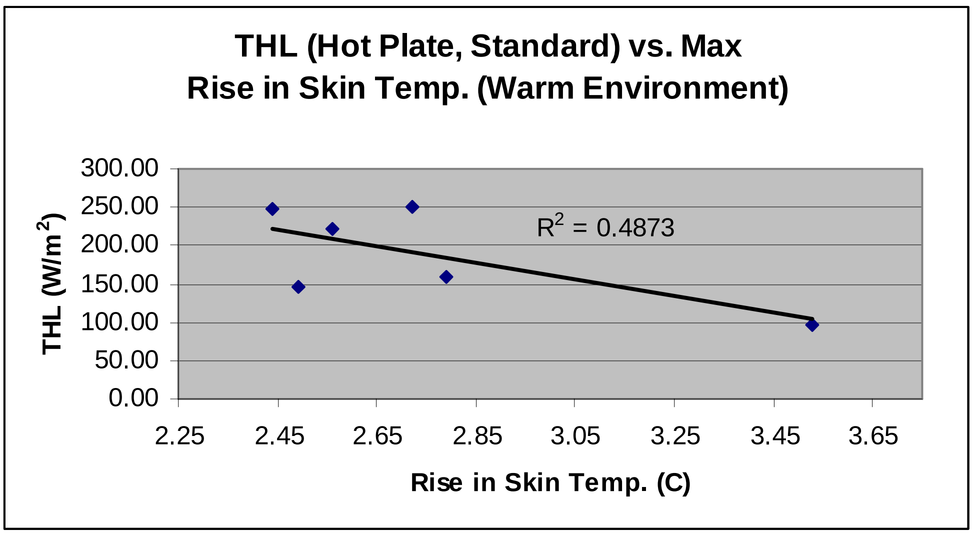



**Figure 4.29: Vague Correlation between Skin Temperature Response for the Warm Environment Protocol and Total Heat Loss Predicted by the Hot Plate (Standard Conditions)**

In this case, the correlation is much less strong because the rather large differences in THL don't match up well with the rather small differences in skin temperature response. Fairly similar trends in correlations exist for similar measures of heat loss and skin temperature response (i.e. THL in different conditions, evaporative resistance or evaporative heat loss versus skin temperature rise, max skin temperature, average skin temperature). Whatever the case, the indication is basically the same. Correlations are stronger for the manikin basically because differences in the thermal and evaporative resistances are much less for the five breathable garments corresponding to the smaller differences in physiological response. The greater differences between these resistance and heat loss values that are measured on the hot plate are apparently not appreciable in terms of physiological response.

## 4.9 Correlations for Weight Change Results for Wet Testing with the Sweating Manikin

Weight change data helps to assess moisture transport for manikin testing. Overall, the weight change data provided only a minor role in terms of being a valuable supplemental tool for the manikin since it mostly mocked results from power measurement, but with less sophistication. It does, however, show some promise in being useful for certain applications.

### 4.9.1 Correlations for Weight Change Results Measured by Manikin and Water Supply Scales

Manikin weight loss and evaporation rate corresponded very well, as would be expected, with the evaporative resistance and THL measured on the manikin. The inherent relation between water loss (evaporation) and evaporative resistance meant that this weight (water) loss was related to other variables fairly similarly as would be evaporative resistance. The fact that the two methods of measuring evaporative resistance (by power and by weight loss) were so similar is testament to their inherent collinearity. Figure 4.30 shows the agreement of Option 2 and Option 1 with one another.

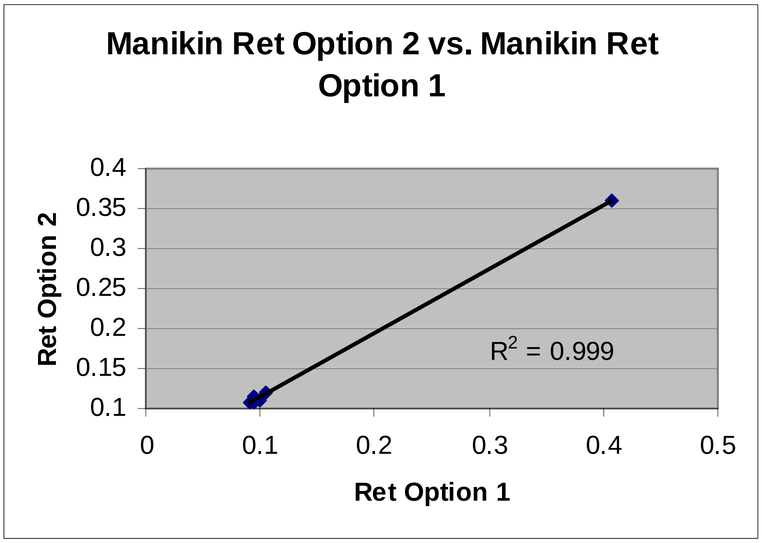



**Figure 4.30: Correlation between Evaporative Resistance Measured by the Manikin via Option 1 and Evaporative Resistance Measured by the Manikin via Option 2**

There are no central points to verify the linear nature of the relationship, but it would be the logical assumption. Also, because all of the values are at either extreme of the overall range and there is only one point on the upper extreme of the range, the $R^2$ value is likely to be substantially inflated. Still, there is good agreement and thus evaporation offers little additional value in terms of relating manikin results to either hot plate or physiological results. There was, however, anticipation that other aspects of the moisture transport may be more useful.

### 4.9.2 Correlations for Weight Change Results Measured by a Digital Scale

There was a desire to know whether the amount of water absorbed in any of the various components of the gear during manikin testing could be a useful predictor of the amount of water absorbed in the various components of the gear during physiological testing. Unfortunately, making this assessment proved to be quite impractical because of the variation in the data. Few statistical differences were found for any components of garment weight gain for the manikin testing and even less were reported for the physiological trial. None of the anticipated comparisons between weight gains in components resulted in significant correlations. Other less likely relationships were found such as, for example, the one shown in Figure 4.31.

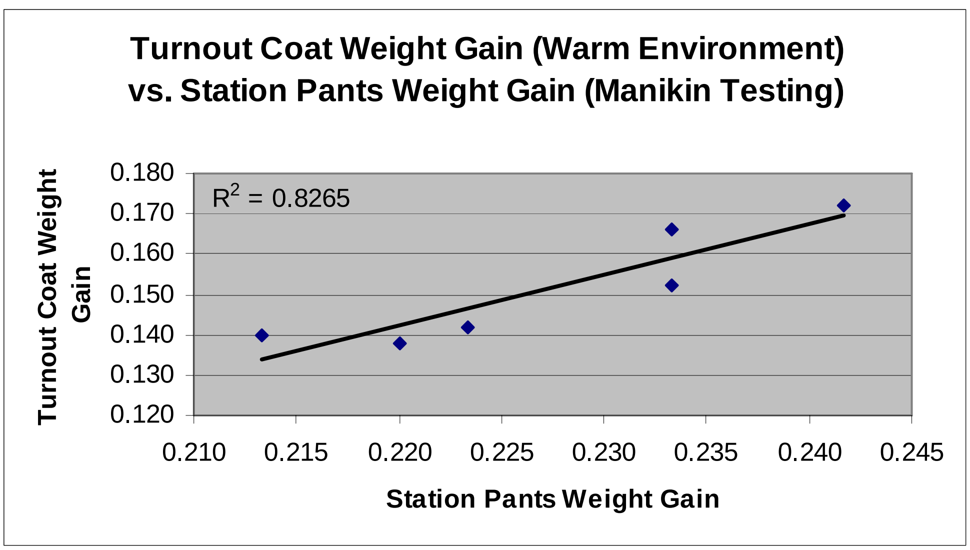



**Figure 4.31: Correlation between Weight Gain of the Station Pants for Manikin Wet Testing and Weight Gain of the Turnout Coat for the Warm Environment Protocol**

However, though there may be some sort of relationship between the two findings, the one found is likely to be largely due to chance. There is little evidence that any of the correlations between weight gains for whichever garment component could be expected to be repeatable. The only relationship that isn't too far-fetched, in terms of being sound enough to have some expectation of repeatability, would be between weight gained in the turnout (physiological testing) and in the station uniform (manikin testing) as shown in Figure 4.32.

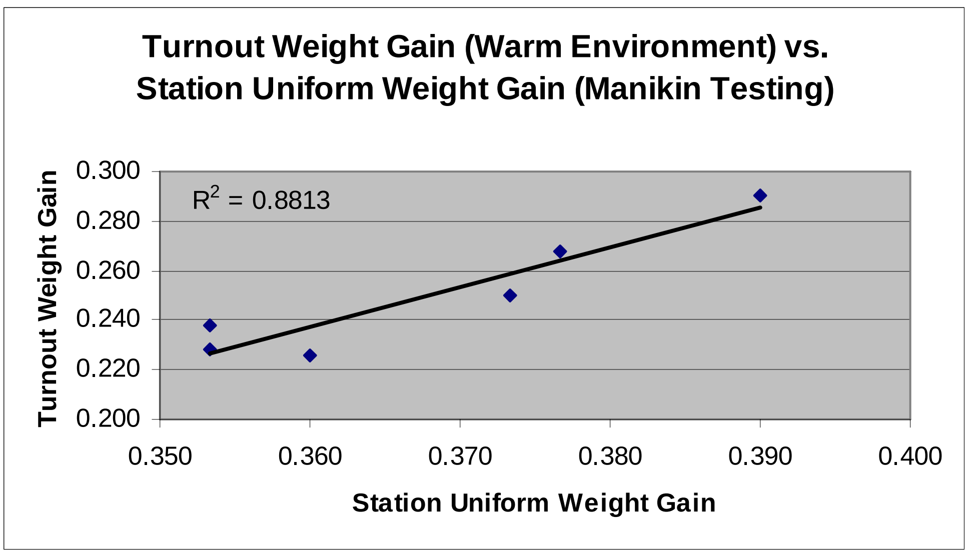



**Figure 4.32: Correlation between Weight Gain of the Station Uniform for Manikin Wet Testing and Weight Gain of the Turnout Suit for the Warm Environment Protocol**

Here, for manikin testing, it could be reasoned that station uniform weight gains could be discriminated for some garments since sweat rates were fairly similar so the variation may be able to be overcome. For physiological testing, it could be that much of the difference in sweat rates between individuals is mitigated by the fact that the underwear and station uniform could be absorbing much of the sweat. If this were the case, the underwear and station uniform weight gains would be expected to be more related to sweat rates than the garment worn. The overall effect would be that the variation because of sweat rate would be most prominent in the layers closest to the skin and less outstanding in the turnout garment itself. So, there is some logic to suggest that such a relationship as show in Figure 4.32 could exist. However, much more testing would be needed to establish any real confidence in the relationship. Yet, if the relationship in Figure 4.32, were shown to exist, other similar relationships such as that shown if Figure 4.31 could be expected as sort of children of that parent relationship.

### 4.9.3 Variation in Weight Change Data

The sweat rate (physiological testing) or the equivalent sweat rate (manikin testing) is probably the most obvious source of unwanted variation when comparing data for weight changes. However, there are several other sources of variation that could affect the results. For physiological testing, the size of the garments and accessories could make a big difference as well as how well they fit. For manikin testing, how similarly the manikin can be dressed and how uniformly the initial 'one shot' spraying can be accomplished could have a significant effect. Also, unlike for heat loss data, where conditions can be modeled from intrinsic resistance values, weight changes are subject to the conditions at which they are measured. Since the wet tests were carried out under isothermal conditions, there is a 4ºC difference between the test conditions for manikin and physiological testing which could make some difference in their compatibility.  The more that can be done to prevent unwanted variation, the more useful the manikin may prove in predicting where and how much moisture is absorbed during physiological testing.

### 4.9.4 Weight Gains of Station Uniforms and Turnout Liners

Overall, there were few statistical differences between weight gains of the different components of the garments.  These differences (reported in the appendix) suggest that much of the overall difference in weight gain may due to the difference recognized in the station uniform and the turnout liner.  Figure 4.33 supports the notion that the weight gain in all gear is largely related to the combined weight gain of the station uniform and turnout liner.

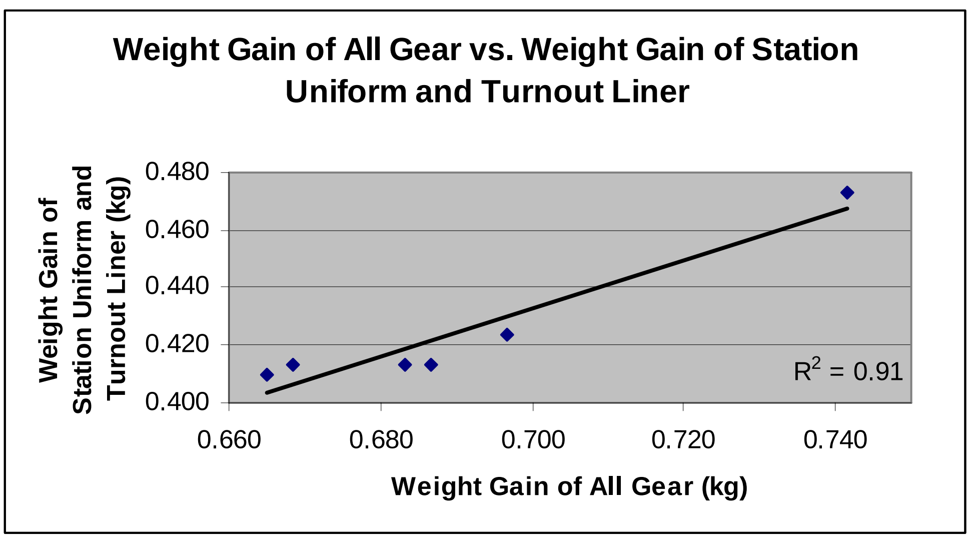



**Figure 4.33: Correlation between Weight Gain of All Gear and Weight Gain of the Station Uniform and Turnout Liner**

As it turns out, the (separate) weight gains of the station uniform and turnout liner (or their pants and top components) were good predictors for several other results including physiological skin temperature responses. However, like manikin weight losses or evaporation rates, the results were just as well correlated with evaporative resistance or similar heat and moisture transfer characteristics. The resultant collinearity (correlation between independent variables) means that the knowing the weight gain of the station uniform or turnout liner gives little additional help in predicting skin temperature response if evaporative resistance (or whatever the other independent variable is) is already known.

### 4.9.5 Summary of the Value of Weight Change Data for the Manikin

Therefore, at this point, there is hardly evidence that weighing the manikin or gear offers any help in predicting physiological response. However, this is not to say that this data is of no value. First off, determining the amount of evaporation is useful for validating other test results. It allows evaporative resistance to be measured in two different ways in order to ensure sound results. The amount of sweat able to be lost to the environment, also, may provide a more tangible result for many who may not appreciate the concept of evaporative resistance or total heat loss. Secondly, by weighing each component of the garment, one can get an idea of where moisture is being trapped as well as identify sources of unwanted variation in the testing. For example, if during one repetition of testing a particular garment one noticed a particular garment component had considerably higher weight gain, it could be an indication that spraying was non-uniform, the manikin was improperly dressed, a sweat valve malfunctioned or some other problem with the test. Finally, although evidence is not strong that weight changes on the manikin can predict weight changes during physiological testing, careful planning to this end could reveal such predictions to be achievable in the future.

### 4.10 Using the Sweating Thermal Manikin to Assess Where Heat Loss Occurs

In addition to the weight of the garment components giving an idea as to how moisture is being transferred at specific locations, the manikin can also measure how much heat is able to be lost for each of the 18 manikin sections individually. By comparing the individual sections within the total range (lowest to highest heat loss for any part for any garment) using a 20 point color scale, one can visually assess where heat loss is taking place both between garments and for different sections within a particular garment ensemble. Figure 4.34 shows such a depiction for the 6 garments tested.

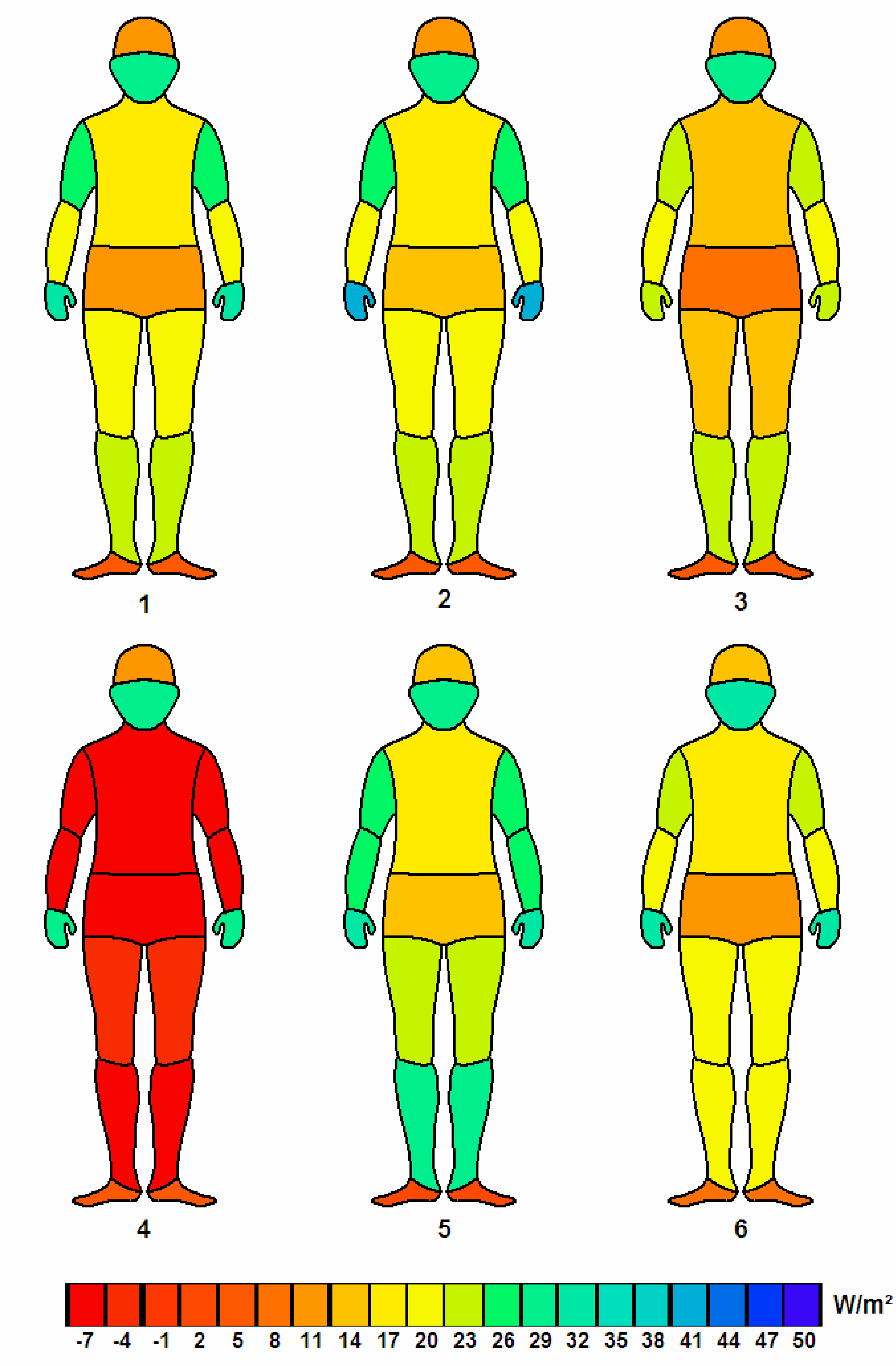



**Figure 4.34: Heat Loss Shown for the Various Segments of the Manikin Using a 20-Point Progressive Color Scale**

The image was created by dividing the total range of heat losses for any part by 20 and then simply assigning colors progressing from warmer to cooler as the total heat loss increases by increments of 1/20 (3 W/m$^2$ in this case) of the total range. Body parts with symmetrical counterparts were averaged and the upper and lower torsos were area-weight averaged for the ventral and dorsal components. This simplification was done since the clothing should be very similar in these areas and it makes it much easier to visually assess the garments. The individual sections with frontal and rear views could also be shown, if desired, to assess variation in testing or if garments which were grossly nonsymmetrical were being evaluated.

In Figure 4.34, Garment 4 appears to be much hotter than any other garment along the entire area covered by the actual garment. The head, hands, and feet, however, appear similar to the other garments as one might expect. The other five garments appear much more similar. It can be noticed that Garments 3 and 6, which have shown evidence of perhaps being slightly hotter, both appear to be slightly warmer in the arms and legs and, in the case of Garment 6, the torso. Garment 5 appears as if it may be slightly cooler than any of the other garments, though differences were not found to be significant. Still, the ability to assess heat loss differences between garments ensembles for individual sections and not just one overall number could be very useful.

One could use the manikin, in this way, not only to better understand how and where heat loss is possible, but also to possibly devise ways in which to improve heat loss in certain areas. The combined information of both where garments were absorbing moisture (from garment weight gains) and where they were losing heat could make the manikin a very useful tool for product developers or design teams interested in improving the heat loss capabilities of their products. The garments evaluated in this case were all fashioned to the same design, so the differences in heat loss for each part are due to material characteristics and error. If one were to instead evaluate different garments made of the same material but of different designs, the implications would be much different. This is probably one of the more obvious and distinct advantages of the manikin over the hot plate. The fire industry has always been very traditional. However, as companies start to come out with new and more innovative designs to meet the growing demands of the industry, garment designs could very well become substantially different from one another. Short of physiological testing, manikins may be the only way to realistically assess heat loss differences when comparing two garments which are substantially dissimilar in design.

## Chapter 5: Conclusions and Recommendations

### 5.1 Summary of Results

Overall, results from manikin testing seemed to be in much better agreement with physiological responses than were hot plate results. The hot plate appears to exaggerate material properties, not taking into account extra clothing and air layers or other aspects of garment design. In certain conditions, therefore, differences that are easily recognizable on the hot plate may not be appreciable to the wearer. The manikin reflects this notion by the manner in which clearly distinguishable results on the hot plate are not necessarily so on the manikin. With the addition of the station uniform, extra air layers, and other aspects of garment design, all of the differences in thermal resistance measured on the sweating hot plate were defeated on the manikin. For evaporative resistance, three clearly distinguishable levels of resistance measured on the hot plate were reduced to only two obviously distinct levels on the manikin. These levels corresponded to the one non-breathable garment (high resistance) and the five breathable garments (low resistance).

Thus, within the range of materials tested, only evaporative resistance had an appreciable effect in terms of making a difference in total heat loss. Thus, there was only one garment with a total heat loss plainly different from the others. This garment, the non-breathable Garment 4, was also recognized as being the only garment to provoke significantly different physiological responses during the wear trial. The fact that for both manikin and physiological results, there were, for the most part, only two levels for the response variables and that they were very unbalanced, made it difficult to confidently define relationships between the variables. However, manikin and physiological results still correspond quite well with one another. In this fact, there is an implication that the manikin could be used as a tool to help design future wear trials.

## 5.2 Implications for Future Use of the Sweating Manikin

If the goal of your trial was to be able to develop relationships between physiological response and manikin or hot plate results, the manikin could be used to first determine whether results were clearly distinguishable before setting up a much more expensive wear trial. Furthermore, it could be used to help establish that an appropriate range and spread of values was achieved in order to expect that physiological responses could be differentiated. The ability to dress the manikin as it would be during the trial and to model the conditions for the trial makes it a very versatile tool for adapting to different protocols.

Because thermal resistances were not differentiable on the manikin for the range of materials used in this trial, it is more difficult to assess what advantage is offered by modeling the total heat loss for the actual conditions over using the standard conditions. This is because dry heat loss was basically taken out of the equation since it was essentially equal for all of the garments regardless of the conditions. The result was that, in this situation, differences for the standard and modeled conditions were fairly similar in terms of relative differences between garments. There was some dependence on difference in the evaporative resistance for the different humidities, but it was relatively small since all standard condition results could be achieved by simply adding approximately 40-50 W/m² to the results modeled for the Warm Environment conditions. In the future, selecting garments with substantially different thermal resistances could help to better define the advantage of modeling for different conditions. As of now, the results are fairly inconclusive. The only thing that can really be said for the total heat loss predicted for the Warm Environment conditions opposed to standard conditions is that the range may be more appropriate; this was evidenced by the fact that the body's ability to recover during rest was better predicted by the Warm Environment THL than the standard condition THL.

Regardless of how THL is modeled, there are obvious advantages of the manikin that are impossible to realize on the hot plate. Particularly different garment designs can be evaluated and heat loss can be modeled by the section on the manikin. This is helpful for researchers in evaluating not just which garment designs may facilitate more heat loss but how and where heat is able to best escape. For this, the manikin could not only be an important tool for researchers, but for product designers or marketers wanting to get an edge up on their competition as well.

Besides being a tool for researchers or designers, the results of this study could also have implications about the manikin as a useful tool for setting performance requirements. Results have shown that differences in results measured on the hot plate may very well be unappreciable in reality. Compromising protection and/or performance in order reach superficial heat loss goals would be a tragedy for all of the fire industry. It is important, then, to assure that heat loss goals remain meaningful by validating that differences in hot plate values can be appreciated by the firefighter. The sweating manikin can play an important role as a means toward that end. The manikin has shown, at least in this instance, to be in good agreement with physiological findings. Differences in individual responses always makes assessing physiological data somewhat complicated. However, with carefully designed studies and a continued research effort clearer relationships between physiological results and manikin results are completely reasonable. The manikin has demonstrated some obvious advantages over the sweating hot plate. So, as the fire industry continues to grow and change, the manikin could very well play an increasing role in helping set new performance requirements as long as heat stress continues to be a concern.

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# APPENDIX

# Appendix

## A.1 Differences of Garments in Response to Various Factors

Two of the more commonly used multiple comparison procedures (Fisher's Least Significant Difference and Tukey's Honest Significant Difference) were used to analyze all results. These multiple comparison procedures were used since there were 6 treatments, in most cases, which greatly increasing the chance that at least one comparison would result in detecting a significant effect when in fact there was none (Type I error) if the 15 single t-test comparisons were made.

Tukey's Honest Significant Difference (HSD) Test is a conservative approach which controls the experiment-wise error rate [72]. Tukey's HSD Test is commonly used to detect differences that one can be confident actually exist since it reduces the chance of Type I error. Type I error is reduced because each comparison's error rate is reduced in order to control the chance of a single error occurring for the entire experiment [72].

Fisher's Least Significant Difference (LSD) Test controls comparison-wise error rates and is more commonly used when one wants to be sure to detect a difference, if it exists. Fisher's LSD Test actually yields the same results that one would get from a series of t-tests, except that no comparisons are made if the F-statistic from a one-way analysis of variance doesn't indicate that at least one difference exists [72]. The chance of making a Type I error is somewhat greater with this method, but the chance of making a Type II error (failing to determine a difference when one actually exists) is reduced.

Tukey's HSD is used here to detect differences that can be accepted confidently. Differences determined by **Tukey's HSD** test are indicated by **bold-face** typing in

Appendix A. Since Fisher's LSD has a greater chance of Type I error, it will determine all of the same differences as Tukey's HSD test and may determine other differences also to exist. Additional differences determined by *Fisher's LSD* test are indicated by *italics* throughout Appendix A. Thus, when reading Appendix A, differences highlighted in **bold** could be read as "**very likely**" to exist and differences highlighted in *italics* could be read as "*fairly likely*" to exist. All tests were carried out using a 95% ($\alpha = 0.05$) confidence level.

### A.1.1 Manikin Heat Transfer Data

**Table A.1: Differences of Garments in Thermal Resistance measured on the Manikin**

| | **Garment** | | | | |
|---|---|---|---|---|---|
| | **2** | **3** | **4** | **5** | **6** |
| **1** | 0 | 0 | 0 | 0 | 0 |
| **2** | | 0 | 0 | 0 | 0 |
| **3** | | | 0 | 0 | *6 > 3* |
| **4** | | | | 0 | 0 |
| **5** | | | | | 0 |

**Table A.2: Differences of Garments in Evaporative Resistance measured on the Manikin**

| | **Garment** | | | | |
|---|---|---|---|---|---|
| | **2** | **3** | **4** | **5** | **6** |
| **1** | 0 | 0 | **4 > 1** | 0 | 0 |
| **2** | | 0 | **4 > 2** | 0 | 0 |
| **3** | | | **4 > 3** | *3 > 5* | 0 |
| **4** | | | | **4 > 5** | **4 > 6** |
| **5** | | | | | 0 |

**Table A.3: Differences of Garments in Evaporative Resistance measured on the Manikin via Option 2**

| | Garment | | | | |
|---|---|---|---|---|---|
| | **2** | **3** | **4** | **5** | **6** |
| **1** | 0 | 0 | **4 > 1** | 0 | 0 |
| **2** | | 0 | **4 > 2** | 0 | 0 |
| **3** | | | **4 > 3** | 0 | 0 |
| **4** | | | | **4 > 5** | **4 > 6** |
| **5** | | | | | 0 |

## A.1.2 Manikin Data – Standard Conditions (25ºC, 65% RH)

**Table A.4: Differences of Garments in Total Heat Loss Predicted by the Manikin for 25ºC, 65% RH**

| | Garment | | | | |
|---|---|---|---|---|---|
| | **2** | **3** | **4** | **5** | **6** |
| **1** | 0 | 0 | **1 > 4** | *5 > 1* | 0 |
| **2** | | 0 | **2 > 4** | *5 > 2* | 0 |
| **3** | | | **3 > 4** | 0 | 0 |
| **4** | | | | **5 > 4** | **6 > 4** |
| **5** | | | | | *5 > 6* |

**Table A.5: Differences of Garments in Dry Heat Loss Predicted by the Manikin for 25ºC, 65% RH**

| | Garment | | | | |
|---|---|---|---|---|---|
| | **2** | **3** | **4** | **5** | **6** |
| **1** | 0 | 0 | 0 | 0 | 0 |
| **2** | | 0 | 0 | 0 | 0 |
| **3** | | | 0 | 0 | *3 > 6* |
| **4** | | | | 0 | 0 |
| **5** | | | | | 0 |

**Table A.6: Differences of Garments in Evaporative Heat Loss Predicted by the Manikin for 25ºC, 65% RH**

| Garment | | | | | |
|---|---|---|---|---|---|
| | **2** | **3** | **4** | **5** | **6** |
| **1** | 0 | 0 | **1 > 4** | *5 > 1* | 0 |
| **2** | | 0 | **2 > 4** | *5 > 2* | 0 |
| **3** | | | **3 > 4** | *5 >3* | 0 |
| **4** | | | | **5 > 4** | **6 > 4** |
| **5** | | | | | *5 > 6* |

### A.1.3 Manikin Data – International Firefighter Protective Clothing Breathability Research Project, Warm Environment Protocol Conditions (39ºC, 35% RH)

**Table A.7: Differences of Garments in Total Heat Loss Predicted by the Manikin for 39ºC, 35% RH**

| Garment | | | | | |
|---|---|---|---|---|---|
| | **2** | **3** | **4** | **5** | **6** |
| **1** | 0 | **1 > 3** | **1 > 4** | *5 > 1* | 0 |
| **2** | | **2 > 3** | **2 > 4** | 0 | 0 |
| **3** | | | **3 > 4** | **5 > 3** | **6 > 3** |
| **4** | | | | **5 > 4** | **6 > 4** |
| **5** | | | | | **5 > 6** |

**Table A.8: Differences of Garments in Dry Heat Loss Predicted by the Manikin for 39ºC, 35% RH**

| Garment | | | | | |
|---|---|---|---|---|---|
| | **2** | **3** | **4** | **5** | **6** |
| **1** | 0 | 0 | 0 | 0 | 0 |
| **2** | | 0 | 0 | 0 | 0 |
| **3** | | | 0 | 0 | *6 > 3* |
| **4** | | | | 0 | 0 |
| **5** | | | | | 0 |

**Table A.9: Differences of Garments in Evaporative Heat Loss Predicted by the Manikin for 39ºC, 35% RH**

| | Garment | | | | |
|---|---|---|---|---|---|
| | **2** | **3** | **4** | **5** | **6** |
| **1** | 0 | **1 > 3** | **1 > 4** | *5 > 1* | *1 > 6* |
| **2** | | **2 > 3** | **2 > 4** | 0 | *2 > 6* |
| **3** | | | **3 > 4** | **5 > 3** | 0 |
| **4** | | | | **5 > 4** | **6 > 4** |
| **5** | | | | | **5 > 6** |

### A.1.4 Hot Plate Heat Transfer Data

**Table A.10: Differences of Garments in Thermal Resistance measured on the Hot Plate**

| | Garment | | | | |
|---|---|---|---|---|---|
| | **2** | **3** | **4** | **5** | **6** |
| **1** | **2 > 1** | **3 > 1** | **4 > 1** | 0 | 0 |
| **2** | | 0 | **2 > 4** | **2 > 5** | **2 > 6** |
| **3** | | | **3 > 4** | **3 > 5** | **3 > 6** |
| **4** | | | | **4 > 5** | **4 > 6** |
| **5** | | | | | 0 |

**Table A.11: Differences of Garments in Evaporative Resistance measured on the Hot Plate**

| | Garment | | | | |
|---|---|---|---|---|---|
| | **2** | **3** | **4** | **5** | **6** |
| **1** | 0 | **3 > 1** | **4 > 1** | 0 | **6 > 1** |
| **2** | | **3 > 2** | **4 > 2** | 0 | **6 > 2** |
| **3** | | | **4 > 3** | **3 > 5** | 0 |
| **4** | | | | **4 > 5** | **4 > 6** |
| **5** | | | | | **6 > 5** |

### A.1.5 Hot Plate Data – Standard Conditions (25ºC, 65% RH)

**Table A.12: Differences of Garments in Total Heat Loss Predicted by the Hot Plate for 25ºC, 65% RH**

| Garment | | | | | |
|---|---|---|---|---|---|
| | **2** | **3** | **4** | **5** | **6** |
| **1** | **1 > 2** | **1 > 3** | **1 > 4** | 0 | **1 > 6** |
| **2** | | **2 > 3** | **2 > 4** | **5 > 2** | **2 > 6** |
| **3** | | | **3 > 4** | **5 > 3** | **6 > 3** |
| **4** | | | | **5 > 4** | **6 > 4** |
| **5** | | | | | **5 > 6** |

**Table A.13: Differences of Garments in Dry Heat Loss Predicted by the Hot Plate for 25ºC, 65% RH**

| Garment | | | | | |
|---|---|---|---|---|---|
| | **2** | **3** | **4** | **5** | **6** |
| **1** | **1 > 2** | **1 > 3** | **1 > 4** | 0 | 0 |
| **2** | | 0 | **4 > 2** | **5 > 2** | **6 > 2** |
| **3** | | | **4 > 3** | **5 > 3** | **6 > 3** |
| **4** | | | | **5 > 4** | **6 > 4** |
| **5** | | | | | 0 |

**Table A.14: Differences of Garments in Evaporative Heat Loss Predicted by the Hot Plate for 25ºC, 65% RH**

| Garment | | | | | |
|---|---|---|---|---|---|
| | **2** | **3** | **4** | **5** | **6** |
| **1** | **1 > 2** | **1 > 3** | **1 > 4** | 0 | **1 > 6** |
| **2** | | **2 > 3** | **2 > 4** | *5 > 2* | **2 > 6** |
| **3** | | | **3 > 4** | **5 > 3** | **6 > 4** |
| **4** | | | | **5 > 4** | 0 |
| **5** | | | | | **5 > 6** |

**A.1.6 Manikin Data – International Firefighter Protective Clothing Breathability Research Project, Warm Environment Protocol Conditions (39ºC, 35% RH)**

**Table A.15: Differences of Garments in Total Heat Loss Predicted by the Hot Plate for 39ºC, 35% RH**

| | Garment | | | | |
|---|---|---|---|---|---|
| | **2** | **3** | **4** | **5** | **6** |
| **1** | *1 > 2* | **1 > 3** | **1 > 4** | 0 | **1 > 6** |
| **2** | | **2 > 3** | **2 > 4** | 0 | **2 > 6** |
| **3** | | | **3 > 4** | **5 > 3** | *3 > 6* |
| **4** | | | | **5 > 4** | **6 > 4** |
| **5** | | | | | **5 > 6** |

**Table A.16: Differences of Garments in Dry Heat Loss Predicted by the Hot Plate for 39ºC, 35% RH**

| | Garment | | | | |
|---|---|---|---|---|---|
| | **2** | **3** | **4** | **5** | **6** |
| **1** | **2 > 1** | **3 > 1** | **4 > 1** | 0 | 0 |
| **2** | | 0 | **2 > 4** | **2 > 5** | **2 > 6** |
| **3** | | | **3 > 4** | **3 > 5** | **3 > 6** |
| **4** | | | | **4 > 5** | **4 > 6** |
| **5** | | | | | 0 |

**Table A.17: Differences of Garments in Evaporative Heat Loss Predicted by the Hot Plate for 39ºC, 35% RH**

| | Garment | | | | |
|---|---|---|---|---|---|
| | **2** | **3** | **4** | **5** | **6** |
| **1** | **1 > 2** | **1 > 3** | **1 > 4** | 0 | **1 > 6** |
| **2** | | **2 > 3** | **2 > 4** | **5 > 2** | **2 > 6** |
| **3** | | | **3 > 4** | **5 > 3** | 0 |
| **4** | | | | **5 > 4** | **6 > 4** |
| **5** | | | | | **5 > 6** |

### A.1.7 Weight Data – Manikin Testing

**Table A.18: Differences of Garments in Equivalent Sweat Rate measured by Manikin Scale and Water Supply Scale**

| | **Garment** | | | | |
|---|---|---|---|---|---|
| | **2** | **3** | **4** | **5** | **6** |
| **1** | 0 | 0 | 0 | 0 | 0 |
| **2** | | 0 | 0 | 0 | 0 |
| **3** | | | 0 | 0 | 0 |
| **4** | | | | 0 | 0 |
| **5** | | | | | 0 |

**Table A.19: Differences of Garments in Evaporation Rate measured by Manikin Scale and Water Supply Scale**

| | **Garment** | | | | |
|---|---|---|---|---|---|
| | **2** | **3** | **4** | **5** | **6** |
| **1** | 0 | **1 > 3** | **1 > 4** | 0 | 0 |
| **2** | | 0 | **2 > 4** | 0 | 0 |
| **3** | | | **3 > 4** | **5 > 3** | *6 > 3* |
| **4** | | | | **5 > 4** | **6 > 4** |
| **5** | | | | | 0 |

**Table A.20: Differences of Garments in Percent of Sweat Evaporated measured by Manikin Scale and Water Supply Scale**

| | **Garment** | | | | |
|---|---|---|---|---|---|
| | **2** | **3** | **4** | **5** | **6** |
| **1** | 0 | *1 > 3* | **1 > 4** | 0 | 0 |
| **2** | | 0 | **2 > 4** | 0 | 0 |
| **3** | | | **3 > 5** | 0 | **6 > 3** |
| **4** | | | | **5 > 4** | **6 > 4** |
| **5** | | | | | 0 |

**Table A.21: Differences of Garments in Water Accumulation in Gear measured by Manikin Scale and Water Supply Scale**

| Garment | | | | | |
|---|---|---|---|---|---|
| | **2** | **3** | **4** | **5** | **6** |
| **1** | 0 | 0 | 0 | 0 | 0 |
| **2** | | 0 | *4 > 2* | 0 | 0 |
| **3** | | | *4 > 3* | 0 | 0 |
| **4** | | | | 0 | 0 |
| **5** | | | | | 0 |

### A.1.8 Manikin Weight Loss

**Table A.22: Differences of Garments in Manikin Nude Weight Loss measured by Manikin Scale and Water Supply Scale**

| Garment | | | | | |
|---|---|---|---|---|---|
| | **2** | **3** | **4** | **5** | **6** |
| **1** | 0 | 0 | 0 | 0 | 0 |
| **2** | | 0 | 0 | 0 | 0 |
| **3** | | | 0 | 0 | 0 |
| **4** | | | | 0 | 0 |
| **5** | | | | | 0 |

**Table A.23: Differences of Garments in Manikin Weight Loss in Station Uniform and Socks measured by Manikin Scale and Water Supply Scale**

| Garment | | | | | |
|---|---|---|---|---|---|
| | **2** | **3** | **4** | **5** | **6** |
| **1** | 0 | 0 | 0 | 0 | 0 |
| **2** | | 0 | 0 | 0 | 0 |
| **3** | | | 0 | 0 | 0 |
| **4** | | | | 0 | 0 |
| **5** | | | | | 0 |

**Table A.24: Differences of Garments in Manikin Weight Loss in Underwear measured by Manikin Scale and Water Supply Scale**

| Garment | | | | | |
|---|---|---|---|---|---|
| | **2** | **3** | **4** | **5** | **6** |
| **1** | 0 | *1 > 3* | **1 > 4** | 0 | 0 |
| **2** | | 0 | *2 > 4* | 0 | 0 |
| **3** | | | *3 > 4* | 0 | 0 |
| **4** | | | | **5 > 4** | *6 > 4* |
| **5** | | | | | 0 |

**Table A.25: Differences of Garments in Manikin Weight Loss in Gear (No Harness) measured by Manikin Scale and Water Supply Scale**

| Garment | | | | | |
|---|---|---|---|---|---|
| | **2** | **3** | **4** | **5** | **6** |
| **1** | 0 | 0 | **1 > 4** | 0 | 0 |
| **2** | | 0 | **2 > 4** | 0 | 0 |
| **3** | | | **3 > 4** | 0 | 0 |
| **4** | | | | **5 > 4** | **6 > 4** |
| **5** | | | | | 0 |

**Table A.26: Differences of Garments in Manikin Weight Loss in Gear (With Harness) measured by Manikin Scale and Water Supply Scale**

| Garment | | | | | |
|---|---|---|---|---|---|
| | **2** | **3** | **4** | **5** | **6** |
| **1** | **1 > 2** | **1 > 3** | **1 > 4** | 0 | **1 > 6** |
| **2** | | 0 | **2 > 4** | **5 > 2** | 0 |
| **3** | | | **3 > 4** | **5 > 3** | *6 > 3* |
| **4** | | | | **5 > 4** | **6 > 4** |
| **5** | | | | | **5 > 6** |

### A.1.9 Gear Weight Gain

**Table A.27: Differences of Garments in Turnout Weight Gain**

| | | | Garment | | |
|---|---|---|---|---|---|
| | **2** | **3** | **4** | **5** | **6** |
| **1** | 0 | *1 > 3* | **4 > 1** | 0 | 0 |
| **2** | | 0 | **4 > 2** | 0 | 0 |
| **3** | | | **4 > 3** | *5 > 3* | *6 > 3* |
| **4** | | | | **4 > 5** | 0 |
| **5** | | | | | 0 |

**Table A.28: Differences of Garments in Turnout Coat Weight Gain**

| | | | Garment | | |
|---|---|---|---|---|---|
| | **2** | **3** | **4** | **5** | **6** |
| **1** | 0 | *1 > 3* | **1 > 4** | 0 | 0 |
| **2** | | 0 | **2 > 4** | 0 | 0 |
| **3** | | | **3 > 4** | 0 | **6 > 3** |
| **4** | | | | **5 > 4** | **6 > 4** |
| **5** | | | | | 0 |

**Table A.29: Differences of Garments in Turnout Pants Weight Gain**

| | | | Garment | | |
|---|---|---|---|---|---|
| | **2** | **3** | **4** | **5** | **6** |
| **1** | 0 | **1 > 3** | 0 | 0 | 0 |
| **2** | | **2 > 3** | 0 | 0 | 0 |
| **3** | | | **4 > 3** | **5 > 3** | **6 > 3** |
| **4** | | | | 0 | 0 |
| **5** | | | | | 0 |

**Table A.30: Differences of Garments in Turnout Liner Weight Gain**

| Garment | | | | | |
|---|---|---|---|---|---|
| | **2** | **3** | **4** | **5** | **6** |
| **1** | *1 > 2* | *1 > 3* | **4 > 1** | 0 | 0 |
| **2** | | 0 | **4 > 2** | 0 | 0 |
| **3** | | | **4 > 3** | *5 > 3* | *6 > 3* |
| **4** | | | | **4 > 5** | **4 > 6** |
| **5** | | | | | 0 |

**Table A.31: Differences of Garments in Coat Liner Weight Gain**

| Garment | | | | | |
|---|---|---|---|---|---|
| | **2** | **3** | **4** | **5** | **6** |
| **1** | 0 | 0 | **4 > 1** | 0 | 0 |
| **2** | | 0 | **4 > 2** | 0 | 0 |
| **3** | | | **4 > 3** | 0 | *6 > 3* |
| **4** | | | | **4 > 5** | *4 > 6* |
| **5** | | | | | 0 |

**Table A.32: Differences of Garments in Pants Liner Weight Gain**

| Garment | | | | | |
|---|---|---|---|---|---|
| | **2** | **3** | **4** | **5** | **6** |
| **1** | 0 | 0 | 0 | 0 | 0 |
| **2** | | 0 | *4 > 2* | 0 | 0 |
| **3** | | | *4 > 3* | 0 | 0 |
| **4** | | | | 0 | 0 |
| **5** | | | | | 0 |

**Table A.33: Differences of Garments in Station Uniform Weight Gain**

| Garment | | | | | |
|---|---|---|---|---|---|
| | **2** | **3** | **4** | **5** | **6** |
| **1** | 0 | 0 | 0 | 0 | 0 |
| **2** | | 0 | 0 | 0 | 0 |
| **3** | | | 0 | 0 | 0 |
| **4** | | | | 0 | 0 |
| **5** | | | | | 0 |

**Table A.34: Differences of Garments in Station Shirt Weight Gain**

| Garment | | | | | |
|---|---|---|---|---|---|
| | **2** | **3** | **4** | **5** | **6** |
| **1** | 0 | 0 | *4 > 1* | 0 | 0 |
| **2** | | 0 | 0 | 0 | 0 |
| **3** | | | *4 >3* | 0 | 0 |
| **4** | | | | *4 > 5* | *4 > 6* |
| **5** | | | | | 0 |

**Table A.35: Differences of Garments in Station Pants Weight Gain**

| Garment | | | | | |
|---|---|---|---|---|---|
| | **2** | **3** | **4** | **5** | **6** |
| **1** | 0 | 0 | 0 | 0 | 0 |
| **2** | | 0 | 0 | 0 | 0 |
| **3** | | | 0 | 0 | 0 |
| **4** | | | | 0 | 0 |
| **5** | | | | | 0 |

**Table A.36: Differences of Garments in Helmet Weight Gain**

| Garment | | | | | |
|---|---|---|---|---|---|
| | **2** | **3** | **4** | **5** | **6** |
| **1** | 0 | 0 | 0 | 0 | 0 |
| **2** | | 0 | 0 | 0 | 0 |
| **3** | | | 0 | 0 | 0 |
| **4** | | | | 0 | 0 |
| **5** | | | | | 0 |

**Table A.37: Differences of Garments in Hood Weight Gain**

| Garment | | | | | |
|---|---|---|---|---|---|
| | **2** | **3** | **4** | **5** | **6** |
| **1** | 0 | 0 | 0 | 0 | 0 |
| **2** | | 0 | 0 | 0 | 0 |
| **3** | | | 0 | 0 | 0 |
| **4** | | | | 0 | 0 |
| **5** | | | | | 0 |

**Table A.38: Differences of Garments in SCBA Facepiece Weight Gain**

| Garment | | | | | |
|---|---|---|---|---|---|
| | **2** | **3** | **4** | **5** | **6** |
| **1** | 0 | 0 | 0 | 0 | 0 |
| **2** | | 0 | 0 | 0 | 0 |
| **3** | | | 0 | 0 | 0 |
| **4** | | | | 0 | 0 |
| **5** | | | | | 0 |

**Table A.39: Differences of Garments in Gloves Weight Gain**

| Garment | | | | | |
|---|---|---|---|---|---|
| | **2** | **3** | **4** | **5** | **6** |
| **1** | *1 > 2* | 0 | 0 | 0 | *1 > 6* |
| **2** | | 0 | 0 | 0 | 0 |
| **3** | | | 0 | 0 | 0 |
| **4** | | | | 0 | 0 |
| **5** | | | | | 0 |

**Table A.40: Differences of Garments in Shoes Weight Gain**

| Garment | | | | | |
|---|---|---|---|---|---|
| | **2** | **3** | **4** | **5** | **6** |
| **1** | 0 | 0 | 0 | 0 | 0 |
| **2** | | 0 | 0 | 0 | 0 |
| **3** | | | 0 | 0 | 0 |
| **4** | | | | 0 | 0 |
| **5** | | | | | 0 |

**Table A.41: Differences of Garments in Underwear Weight Gain**

| Garment | | | | | |
|---|---|---|---|---|---|
| | **2** | **3** | **4** | **5** | **6** |
| **1** | 0 | 0 | 0 | 0 | 0 |
| **2** | | 0 | 0 | 0 | 0 |
| **3** | | | 0 | 0 | 0 |
| **4** | | | | 0 | 0 |
| **5** | | | | | 0 |

**Table A.42: Differences of Garments in Socks Weight Gain**

| | Garment | | | | |
|---|---|---|---|---|---|
| | **2** | **3** | **4** | **5** | **6** |
| **1** | 0 | 0 | 0 | 0 | 0 |
| **2** | | 0 | 0 | 0 | *2 > 6* |
| **3** | | | 0 | 0 | 0 |
| **4** | | | | 0 | 0 |
| **5** | | | | | 0 |

**Table A.43: Differences of Garments in Accessory Weight Gain**

| | Garment | | | | |
|---|---|---|---|---|---|
| | **2** | **3** | **4** | **5** | **6** |
| **1** | 0 | 0 | 0 | 0 | 0 |
| **2** | | 0 | 0 | 0 | 0 |
| **3** | | | 0 | 0 | 0 |
| **4** | | | | 0 | 0 |
| **5** | | | | | 0 |

## A.2 Regression Diagnostics

Many correlations were found between the various data parameters. However, in analyzing the data, there were several concerns about the validity of the relationships. In particular, there was some evidence in the nature of the errors that indicated that some of the data may not meet the regression assumptions; there was also concern about the distribution of data in that some points may have undue influence on the coefficients of correlation.

### A.2.1 Error Assumptions

During analysis, normality plots and plots of residuals vs. fitted values were analyzed to verify that the data was normal (for t-tests to be valid) and that the errors were normally and independently distributed (assumptions of regression). The most noteworthy finding was that in many cases, the assumption of homogeneity of variance (homoscedasticity) appeared to have been violated. Error did not appear to be constant, so a formal test (White's Test) was performed to test the null hypothesis that the variance of the residuals was homogenous [73]. Data that involved physiological responses for the Warm Environment could not be checked for error because of missing data. Other data where correlations warranted further exploration were, however, tested. However, only correlations which were discussed in the body of this work are reported. A summary of the findings is reported in Table A.44.

**Table A.44: Test for Correlation Significance and Heteroscedasticity**

| Comparison | **Pr > F** *Correlation Significance* | **$\chi^2$** *Heteroscedasticity Test Statistic* | **Pr > $\chi^2$** *Significance of Heteroscedasticity* |
|---|---|---|---|
| $R_t$ (Manikin) vs. $R_{ct}$ (Hot Plate) | 0.1053 | 3.53 | 0.1708 |
| $R_{et}$ (Manikin) vs. $AR_{et}$ (Hot Plate) | **<.0001** | 10.65 | **0.0049** |
| THL (Manikin, Standard Conditions) vs. Evaporative Heat Loss (Manikin, Standard Conditions) | **<.0001** | 2.85 | 0.241 |
| THL (Manikin, Standard Conditions) vs. THL (Hot Plate, Standard Conditions) | **0.0007** | 7.82 | **0.0201** |
| THL (Manikin, Warm Conditions) vs. THL (Hot Plate, Warm Conditions) | **<.0001** | 11.8 | **0.0027** |
| $R_{et}$ Option 2 (Manikin) vs. $R_{et}$ Option 1 (Manikin) | **<.0001** | 3.68 | 0.165 |
| Weight Gain of All Gear (Manikin) vs. Weight Gain of Station Uniform and Turnout Liner (Manikin) | **0.0001** | 2.96 | 0.2271 |

The furthest right column in Table A.44 is an indication of the level of significant heteroscedasticity detected. Slight heteroscedasticity may not affect results greatly, but strong heteroscedasticity can seriously distort the findings and weaken analysis [74]. All of the correlations reported in Table A.44 were significant with the exception of 'Rt (Manikin) vs. Rct (Hot Plate)' as expected, however nearly half of them showed to have problems with the assumption of homogeneity of variance.

### A.2.2 Influential Data

The distribution of data is important in its analysis. A single observation (or small group of observations) can seriously alter regression analysis if it is substantially different from all other observations [75]. When this occurs, it is important to try to understand why this is happening and what it might indicate about the results. There are three basic categorizations of unusual observations: outliers, leverage points, and influential points.

Outliers are observations where the dependent-variable value is unusual given the predictor variables [75]. Outliers are often extreme observations that result from error in data entry, measurement equipment, or other unusual circumstances. Leverage points refer to points where with an extreme value on a predictor variable [75]. Leverage itself is a measure of how an independent variable deviates from its mean. The greater the leverage, the greater the points will affect the regression coefficients. Influence (influential points) is basically a function of leverage and outlierness [75]. A point is considered influential if removing it from the data substantially changes the regression coefficients.

Just by looking at most of the regression data, it is easy to imagine the influence created by the few observation points associated with Garment 4. In many cases the other five garments appear as a conglomerate of points with only Garment 4 discernible because it is so radically different. When the other points can be discerned, the apparent slope of the would-be regression line for the five breathable garments often appears as if it would be much different than the resultant line when the non-breathable garment is included. For this reason it is important to explore the influence of these observations. Tables A.45 – A.51 show the various indicators of influence for each data point for the selected relationships. In the tables, RStudent is the studentized residual which gives a measure of how unusual a point is based on an assumption of normality. All values that are identified as possibly concerning are marked in **bold** in the Tables A.45 – A.51. Criteria for concern were adopted from the proposed cutoff points of Belsley, Kuh, and Welsch [76]. RStudent values greater than 2 warrant further investigation. Leverage of $h_i$ has a cutoff point of 2p/n where p is the number of predictor variables (1) and n is the number of observations. Large values for CovRatio indicate that the point may have excess influence on hypothesis tests and confidence intervals; the cutoff for CovRatio is set for when $|\text{CovRatio} - 1| \geq 3p/n$. DFFITS gives an indication of the influence of a particular point. It is similar to Cook's distance but gives greater consideration to outlying observations; the size-adjusted cutoff for DFFITS is $2*(p/n)^{1/2}$.

**Table A.45: Influential Diagnostics for '$R_t$ (Manikin) vs. $R_{ct}$ (Hot Plate)'**

| $R_t$ (Manikin) vs. $R_{ct}$ (Hot Plate) | | | | | |
|---|---|---|---|---|---|
| Obs | Garment | RStudent | Leverage | CovRatio | DFFITS |
| 1 | 1 | -0.45988 | 0.10408 | **1.23489** | -0.15675 |
| 2 | 1 | -1.04732 | 0.08856 | 1.08399 | -0.32646 |
| 3 | 1 | 0.75481 | 0.08405 | 1.15293 | 0.22864 |
| 4 | 2 | 0.70579 | **0.18446** | **1.30688** | 0.33566 |
| 5 | 2 | 1.97666 | 0.10283 | **0.7982** | **0.66919** |
| 6 | 2 | -1.67537 | 0.08753 | 0.8848 | **-0.51888** |
| 7 | 3 | -1.57728 | **0.23483** | 1.09398 | **-0.87378** |
| 8 | 3 | -0.56964 | **0.15014** | **1.28268** | -0.23942 |
| 9 | 3 | 1.23479 | **0.16664** | 1.12496 | **0.55215** |
| 10 | 4 | 0.44827 | 0.05556 | **1.17307** | 0.10872 |
| 11 | 4 | -1.08093 | 0.05569 | 1.03702 | -0.26249 |
| 12 | 4 | 0.46838 | 0.05615 | **1.17096** | 0.11424 |
| 13 | 5 | -0.64029 | **0.12259** | **1.22866** | -0.23933 |
| 14 | 5 | -0.11516 | **0.12942** | **1.30461** | -0.0444 |
| 15 | 5 | -1.16372 | 0.07987 | 1.04023 | -0.34285 |
| 16 | 6 | 0.9827 | 0.08856 | 1.10188 | 0.30631 |
| 17 | 6 | 0.90942 | 0.0725 | 1.10186 | 0.25426 |
| 18 | 6 | 0.79013 | **0.13658** | **1.21456** | 0.31426 |

**Table A.46: Influential Diagnostics for '$R_{et}$ (Manikin) vs. $AR_{et}$ (Hot Plate)'**

| $R_{et}$ (Manikin) vs. $AR_{et}$ (Hot Plate) | | | | | |
|---|---|---|---|---|---|
| Obs | Garment | RStudent | Leverage | CovRatio | DFFITS |
| 1 | 1 | 0.74753 | 0.08476 | 1.15545 | 0.22748 |
| 2 | 1 | 0.94256 | 0.08476 | 1.108 | 0.28683 |
| 3 | 1 | 0.73818 | 0.08476 | 1.15751 | 0.22464 |
| 4 | 2 | 0.52448 | 0.08163 | **1.19469** | 0.15637 |
| 5 | 2 | 0.53527 | 0.07868 | **1.18908** | 0.15642 |
| 6 | 2 | 0.48571 | 0.07868 | **1.19699** | 0.14194 |
| 7 | 3 | -0.89689 | 0.05644 | 1.08621 | -0.21936 |
| 8 | 3 | -1.6594 | 0.05627 | 0.86063 | -0.40518 |
| 9 | 3 | -1.11056 | 0.05568 | 1.02873 | -0.26966 |
| 10 | 4 | -0.12719 | **0.39383** | **1.87296** | -0.10252 |
| 11 | 4 | 1.14334 | **0.23339** | **1.25577** | **0.63086** |
| 12 | 4 | 1.44415 | **0.29326** | **1.24086** | **0.93028** |
| 13 | 5 | 0.49885 | 0.08163 | **1.1988** | 0.14872 |
| 14 | 5 | 0.51441 | 0.08476 | **1.20041** | 0.15654 |
| 15 | 5 | 0.72758 | 0.08476 | 1.15983 | 0.22141 |
| 16 | 6 | -1.45874 | 0.05556 | 0.92396 | -0.3538 |
| 17 | 6 | -1.41892 | 0.05562 | 0.93651 | -0.34434 |
| 18 | 6 | -1.54827 | 0.05556 | 0.89559 | -0.37552 |

**Table A.47: Influential Diagnostics for 'THL (Manikin, Standard) vs. THL (Hot Plate, Standard)'**

| THL (Manikin, Standard) vs. THL (Hot Plate, Standard) | | | | | |
|---|---|---|---|---|---|
| Obs | Garment | RStudent | Leverage | CovRatio | DFFITS |
| 1 | 1 | -0.66167 | **0.12394** | **1.22613** | -0.24888 |
| 2 | 1 | -0.93226 | **0.12133** | 1.15694 | -0.34642 |
| 3 | 1 | -0.64913 | **0.12049** | **1.22392** | -0.24026 |
| 4 | 2 | -0.13262 | 0.08228 | **1.23688** | -0.03971 |
| 5 | 2 | -0.18604 | 0.07541 | **1.22492** | -0.05313 |
| 6 | 2 | -0.09496 | 0.07642 | **1.23044** | -0.02732 |
| 7 | 3 | **2.13972** | 0.0757 | **0.72255** | **0.61233** |
| 8 | 3 | 0.95287 | 0.09453 | 1.11722 | 0.30788 |
| 9 | 3 | 0.81915 | 0.08076 | 1.13401 | 0.2428 |
| 10 | 4 | -1.20362 | **0.20594** | **1.19159** | **-0.61297** |
| 11 | 4 | -1.60918 | **0.18386** | 1.01384 | **-0.76378** |
| 12 | 4 | -1.66139 | **0.19525** | 1.00852 | **-0.81834** |
| 13 | 5 | 1.07709 | 0.10781 | 1.09873 | 0.37441 |
| 14 | 5 | -0.26291 | **0.12767** | **1.29237** | -0.10058 |
| 15 | 5 | -0.49963 | **0.11967** | **1.25048** | -0.18421 |
| 16 | 6 | 1.81752 | 0.06925 | **0.821** | **0.49578** |
| 17 | 6 | 0.41792 | 0.07349 | **1.19992** | 0.1177 |
| 18 | 6 | 0.50798 | 0.06619 | **1.17757** | 0.13525 |

**Table A.48: Influential Diagnostics for 'THL (Manikin, Warm) vs. THL (Hot Plate, Warm)'**

| THL (Manikin, Warm) vs. THL (Hot Plate, Warm) | | | | | |
|---|---|---|---|---|---|
| Obs | Garment | RStudent | Leverage | CovRatio | DFFITS |
| 1 | 1 | -0.40107 | **0.11357** | **1.25646** | -0.14356 |
| 2 | 1 | -0.79251 | **0.11517** | **1.1846** | -0.28593 |
| 3 | 1 | -0.45529 | **0.1157** | **1.2518** | -0.16468 |
| 4 | 2 | -0.32612 | 0.10924 | **1.25938** | -0.11421 |
| 5 | 2 | -0.25283 | 0.08943 | **1.23894** | -0.07923 |
| 6 | 2 | -0.09729 | 0.08867 | **1.24691** | -0.03035 |
| 7 | 3 | 0.73295 | 0.06447 | 1.13354 | 0.19241 |
| 8 | 3 | 0.94063 | 0.08244 | 1.10571 | 0.28194 |
| 9 | 3 | 0.76588 | 0.07056 | 1.13375 | 0.21103 |
| 10 | 4 | -1.62612 | **0.20332** | 1.03216 | **-0.82149** |
| 11 | 4 | -1.72355 | **0.18248** | 0.96965 | **-0.81429** |
| 12 | 4 | -1.82229 | **0.19095** | 0.94271 | **-0.88531** |
| 13 | 5 | 0.16928 | 0.09223 | **1.2486** | 0.05396 |
| 14 | 5 | 0.06628 | **0.11133** | **1.27957** | 0.02346 |
| 15 | 5 | -0.36912 | **0.11621** | **1.26432** | -0.13385 |
| 16 | 6 | 1.67293 | 0.083 | 0.88124 | **0.50331** |
| 17 | 6 | 1.38604 | 0.08508 | 0.97724 | 0.42267 |
| 18 | 6 | 1.748 | 0.08615 | 0.8593 | **0.53668** |

**Table A.49: Influential Diagnostics for 'THL (Manikin, Standard) vs. Evaporative Heat Loss (Manikin, Standard)'**

| THL (Manikin, Standard) vs. Evaporative Heat Loss (Manikin, Standard) | | | | | |
|---|---|---|---|---|---|
| Obs | Garment | RStudent | Leverage | CovRatio | DFFITS |
| 1 | 1 | -0.12787 | 0.06251 | **1.211** | -0.03302 |
| 2 | 1 | -0.04953 | 0.05681 | **1.20592** | -0.01215 |
| 3 | 1 | -0.12268 | 0.062 | **1.21055** | -0.03154 |
| 4 | 2 | 0.30853 | 0.06364 | **1.19983** | 0.08044 |
| 5 | 2 | 0.35142 | 0.05958 | **1.19018** | 0.08845 |
| 6 | 2 | 0.32097 | 0.06232 | **1.1969** | 0.08275 |
| 7 | 3 | 1.35542 | 0.09304 | 0.99567 | 0.43413 |
| 8 | 3 | 1.75356 | 0.05588 | **0.82996** | 0.42661 |
| 9 | 3 | 1.73547 | 0.05565 | 0.83558 | 0.42129 |
| 10 | 4 | -0.24723 | **0.26745** | 1.54058 | -0.14938 |
| 11 | 4 | -0.184 | **0.30242** | **1.62371** | -0.12116 |
| 12 | 4 | -0.15424 | **0.3193** | **1.6662** | -0.10564 |
| 13 | 5 | -0.09112 | **0.1731** | **1.37443** | -0.04169 |
| 14 | 5 | 0.23649 | 0.07705 | **1.22363** | 0.06833 |
| 15 | 5 | 0.32059 | 0.06449 | **1.19971** | 0.08417 |
| 16 | 6 | **-2.30298** | **0.11167** | **0.69906** | **-0.81654** |
| 17 | 6 | -1.68258 | 0.05558 | 0.85255 | -0.40818 |
| 18 | 6 | -1.76807 | 0.0575 | **0.82671** | -0.43671 |

**Table A.50: Influential Diagnostics for '$R_{et}$ (Manikin Option 2) vs. $R_{et}$ (Manikin Option 1)'**

| $R_{et}$ (Manikin Option 2) vs. $R_{et}$ (Manikin Option 1) | | | | | |
|---|---|---|---|---|---|
| Obs | Garment | RStudent | Leverage | CovRatio | DFFITS |
| 1 | 1 | -0.57523 | 0.06792 | **1.16857** | -0.15528 |
| 2 | 1 | -0.55936 | 0.0652 | **1.16791** | -0.14773 |
| 3 | 1 | 0.31827 | 0.06806 | **1.20455** | 0.08601 |
| 4 | 2 | 0.70985 | 0.06934 | 1.14438 | 0.19377 |
| 5 | 2 | -0.27118 | 0.06714 | **1.20779** | -0.07275 |
| 6 | 2 | 0.68737 | 0.06789 | 1.14724 | 0.18551 |
| 7 | 3 | 0.03416 | 0.06399 | **1.21537** | 0.00893 |
| 8 | 3 | 0.28943 | 0.06279 | **1.20055** | 0.07491 |
| 9 | 3 | 0.11577 | 0.06328 | **1.21248** | 0.03009 |
| 10 | 4 | **-7.89919** | **0.35742** | **0.06651** | **-5.89124** |
| 11 | 4 | 1.22659 | **0.28151** | **1.30803** | 0.76779 |
| 12 | 4 | **3.08631** | **0.35985** | **0.66485** | **2.31396** |
| 13 | 5 | 0.07706 | 0.06977 | **1.22214** | 0.0211 |
| 14 | 5 | 0.32925 | 0.07173 | **1.20818** | 0.09153 |
| 15 | 5 | 0.06278 | 0.06822 | **1.22044** | 0.01699 |
| 16 | 6 | -0.60021 | 0.06565 | 1.16127 | -0.1591 |
| 17 | 6 | -0.14936 | 0.06349 | **1.21131** | -0.03889 |
| 18 | 6 | -0.60748 | 0.06674 | 1.1613 | -0.16245 |

**Table A.51: Influential Diagnostics for 'Weight Gain of All Gear (Manikin) vs. Weight Gain of Station Uniform and Turnout Liner (Manikin)'**

| Weight Gain of All Gear (Manikin) vs. Weight Gain of Station Uniform and Turnout Liner (Manikin) | | | | | |
|---|---|---|---|---|---|
| Obs | Garment | RStudent | Leverage | CovRatio | DFFITS |
| 1 | 1 | 0.33939 | 0.06889 | **1.20341** | 0.09232 |
| 2 | 1 | 0.28486 | 0.09375 | **1.242** | 0.09162 |
| 3 | 1 | -0.23518 | 0.05753 | **1.19837** | -0.0581 |
| 4 | 2 | 0.33939 | 0.06889 | **1.20341** | 0.09232 |
| 5 | 2 | 0.83027 | 0.0973 | 1.15209 | 0.27259 |
| 6 | 2 | -0.12191 | 0.06889 | **1.21954** | -0.03316 |
| 7 | 3 | -1.65747 | 0.0973 | 0.9004 | **-0.54417** |
| 8 | 3 | -0.58846 | 0.06889 | **1.16744** | -0.16007 |
| 9 | 3 | 0.42347 | **0.18182** | **1.35795** | 0.19963 |
| 10 | 4 | -1.31339 | **0.42045** | **1.57914** | **-1.11869** |
| 11 | 4 | 1.43147 | **0.25284** | **1.17875** | **0.83272** |
| 12 | 4 | 1.00481 | 0.07102 | 1.07516 | 0.27783 |
| 13 | 5 | -1.2692 | 0.05682 | 0.98369 | -0.31151 |
| 14 | 5 | **2.71167** | 0.05682 | **0.54321** | **0.66555** |
| 15 | 5 | -0.18231 | 0.09375 | **1.24993** | -0.05864 |
| 16 | 6 | 0.051 | 0.09375 | **1.25504** | 0.0164 |
| 17 | 6 | -1.73152 | 0.09375 | 0.87204 | **-0.55691** |
| 18 | 6 | -0.23518 | 0.05753 | **1.19837** | -0.0581 |

Since correlations can be effected quite severely when one data point (or set of points) lies far outside the range of the other points, assessing the leverage and influence helps to make sense of the data and make careful conclusions. When data points are observed at both extremes of the range with little or no points along the range, variation is minimized and correlations can be strong. However, when this occurs there is little information to verify the linear nature of the relationship or to validate the range of the measurement system. The large amount of concerning statistics for the correlation data means that further investigation would be needed in order to make concrete conclusions concerning those relationships.