ABSTRACT

WALKER, MARIKA AYANA. From Sweating Plates to Manikins: Evaluating the Role of Clothing in Reducing the Risk of Heat Stress in Wildland Firefighting. (Under the direction of Dr. Roger Barker).

This study investigates heat stress in wildland firefighting protective clothing. A sweating hot plate was used to measure the amount of heat dissipated through fabrics, or the total heat loss (THL) through dry and evaporative heat transfer mechanisms. The fabrics characterized in this manner were incorporated into wildland firefighter garments and a sweating manikin was used to measure garment level heat loss. Selected wildland firefighting garments were used in human subject wear trials to measure the effects of garment heat loss on core body temperature and skin temperature. A virtual model framework that was used in the Physiological Modeling Manikin was run separately with sweating manikin inputs and compared back to the results on the physiological manikin and the results of the human wear trial. These data were statistically analyzed to establish correlations between instrument measures at the fabric and garment level. The reciprocal of the total heat loss on the sweating hot plate (1/THL) was shown to provide the best correlation between instrumentation and the physiological human response.

From Sweating Plates to Manikins: Evaluating the Role of Clothing in Reducing the Risk of Heat Stress in Wildland Firefighting

by
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A thesis submitted to the Graduate Faculty of
North Carolina State University
in partial fulfillment of the
requirements for the degree of
Master of Science

Textile Engineering

Raleigh, North Carolina

2013

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DEDICATION

This thesis is dedicated to my mother, Deborah Harry. Without her and God I would not have experienced as much success as I have. Thank you Mommy for all you have done for me to get me this far.

BIOGRAPHY

Marika Ayana Walker was born on November 26, 1989 to Delroy Walker and Deborah Harry. She grew up in Prince Georges County Maryland and attended Eleanor Roosevelt High School where she began her Cross Country and Track career before graduating in 2007.

In August of 2007, she moved to Raleigh, North Carolina and began to attend North Carolina State University on a Cross Country and Track and Field athletic scholarship. She competed in the sport for all four years of her undergraduate career and the first year of her graduate career. As an undergraduate student, she studied Textile Engineering with a Product Development concentration and a minor in Sports Science. Outside of class, in addition to being a student athlete, she worked as a track and field camp counselor during the summers, volunteered in the Children's ministry at World Overcomers Christian Church, and was also very involved on campus. She was a member of Sisters in Sports, a peer instructor in USC 103, a START mentor, the Mentoring and Tutoring chair of Women Empowering Society Together and the president the following year, and the Professional Development Chair of Tau Beta Pi Engineering Honor Society. In addition, in the summer of 2009, Marika worked at Nike IHM in St. Charles, MO as an engineering intern.

In 2011, Marika graduated Magna Cum Laude in Textile Engineering from North Carolina State University with a minor in Sports Science. That summer she began to work at the Textile Protection and Comfort Center (T-PACC) and began research for her Master's thesis project. In the fall of 2011, she began coursework and continued research in the pursuit of a Master of Science in Textile Engineering degree. Throughout her graduate career she worked on a wildland firefighting project sponsored by FEMA. Marika will graduate in the summer of 2013 with the Degree of Master of Science in Textile Engineering.

ACKNOWLEDGMENTS

I would like to thank Dr. Roger Barker, Mr. Kevin Ross, Mr. Shawn Deaton, and Mrs. Gail Liston for their immense help and guidance in my research. I would also like to thank FEMA in the Department of Homeland Security for sponsoring the project that my research was based on. I would also like to thank my coworkers in the Textile Protection and Comfort Center, Candace Rubenstein, Jeremy Lewis, Kyle Watson, Julisha Joyner, Ashley Bradham, William Gabler, Alex Hummel, and Bryan Ormond for their help and support in conducting my research. Finally, I would like to thank my family and friends, especially my mother and father, for their support during my graduate and undergraduate career.

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1 Introduction

Wildland firefighters face competing hazards when they are wearing their garments. One obvious hazard is the risk of burn injuries while another hazard involves the buildup of heat in the body. As additional fire-resistive material is added to the garments, the ability of the body to release the heat can be impeded[1]. There is concern that garments may exceed the amount of protection needed and become a burden with regard to heat stress[2]. According to Al Beaver of the Yukon Fire Management Division, "Current firefighter PPE provides sufficient protection in suppressing wildland fires up to the intensity for which direct and parallel suppression tactics may be effective. Further armoring the firefighter in this respect serves only to increase their exposure/risk to heat stress without an increase in the fire suppression reward"[3].

There are no typical environments for wildland firefighters. Their garments must be versatile to prepare them for any environment that they may encounter. Their primary thermal hazard comes from radiant heat[4]. Researchers have begun to look at optimizing a garment for wildland firefighting but there is still plenty of work to be done.

1.1 Research Objectives

The purpose of this research is to investigate how heat stress in wildland firefighting garments correlates with laboratory test methods for measuring heat loss. This will be accomplished by simulating wildland firefighting conditions in a physiological wear trial in order to study the effects of different clothing materials on heat stress. These measures will be correlated with the sweating manikin and the other instrumented tests. This research has the following specific objectives:

1. To qualify the effect of protective fabric materials and clothing on wildland firefighter heat stress
2. To establish correlations between fabric and garment measures of heat stress using an instrumented sweating manikin
3. To conduct a laboratory study of the effects of clothing on human physiological response using a wear protocol designed for wildland use conditions
4. To compare material level heat stress predictions to human response
5. To compare systems level heat stress predictions to human response using sophisticated virtual modeling techniques

Achievement of these objectives will allow validation of a heat transfer virtual model and a physiological sweating manikin.

2 Literature Review

2.1 Need for Research

A publication from the National Wildfire Coordinating Group entitled "Wildland Firefighter Fatalities in the United States: 1990-2006" shows that 22.5 percent of the deaths experienced by wildland firefighters came from heart attacks from the years of 1999 through 2006. This cause of death was tied with aircraft accidents for the 2nd most common type of death, behind vehicle accidents (26.6%). Heart attacks are often associated with poor physical fitness. This is due to the faster buildup of metabolic heat that is sustained when doing the same amount of work as someone with better physical fitness[5]. Fit workers have a slower buildup of metabolic heat because they have a better circulatory system and therefore can regulate the body temperature better. They can adjust to the heat about twice as fast as an ordinary unfit worker[6]. Heat stress is cited as a separate cause of death in another category entitled Medical Causes other than Heart Attacks(3%)[5].

A notable death in relation to heat stress in wildland firefighting occurred in the summer of 2011[7]. Caleb Mann, a fit 23 year old firefighter in the Interagency Hot Shot Crew in Utah, died on July 7, 2011 from heat stress after fighting a wildland fire in Texas. He had been fighting a wildland fire in Georgia for several days and then had to travel to Texas to begin fighting this fire. Mann was found unconscious after being left alone for a short period of time during construction of a fire line[7]. By the time Mann arrived at the hospital, he had a recorded core temperature of 108°F. It was later reported that many of the men were hot, nauseated, dizzy, and had headaches the night before fighting the fires. These are all symptoms associated with moderate heat illness. This case shows that death from heat stress doesn't happen very often but it does occur, and is often masked by other causes of death.

In terms of death associated with protection from the fire, burnovers with 21% of deaths were the most significant[5]. These are not necessarily related to heat stress, but can be because heat stress causes short term and long term fatigue which may be attributed to the deaths that occur from burnovers. Burnovers occur when wildfires rapidly spread and firefighters must retreat to their shelters. When this happens, firefighters must deploy their protective tents and go into them until the fire is tame enough for them to come out. Sometimes, firefighters are not able to set up their shelters fast enough and are engulfed by the fire, resulting in them being burned to death. Also, in many cases, the fire around the shelter is so extreme that it may burn the firefighters or the shelter will protect them from some heat but will not protect from the hot air that the firefighters must inhale, causing most to die anyway[8]. Some research in garment design has targeted an increase in protection in order to decrease the amount of injuries from burns and deaths from burnover. In the case where the fire is this extreme, no amount of realistic insulation in their garments would protect them from death. Deaths that have occurred due to this phenomenon have decreased over time likely due to an improved protocol that keeps firefighters further away from the fireline. However, since the number of burnovers decreased and the amount of protection has increased, it seems as if increasing protection in the garment has contributed to the decrease. The number of heart attacks that are occurring is also increasing. This increase is likely due to the increased protection within the garments[5]. A study conducted by Budd and

Brotherhood et al. entitled “Project Aquarius 6: Heat load from exertion, weather, and fire in men suppressing wildland fires,” which measured numerous wildland firefighters’ thermal environments while they suppressed experimental bushfires, showed that the conditions near a fire were not significantly different from the conditions away from the fire. Therefore, it was concluded that the increase of heat buildup can be attributed more to the firefighters own metabolic heat than the heat of the fire itself[9].

An increase in heat stress reduces mental performance and therefore slows reaction time and decision time and sometimes affects decision making altogether[10]. The previously mentioned burnovers involve the quick retreat of the firefighters to set up and get inside of their shelter. If they are suffering from heat stress, it may cause the firefighters to move slower and therefore lead to more fatalities in the burnover category[10]. As far as injuries that are not life threatening, the most common are slips, trips, and falls. Many of these accidents have been attributed to short term and long term fatigue[11]. Since heat stress as well as a lack of fitness is a common cause of fatigue, it is possible that a reduction in the thermal burden of the garments could cause a decrease in these injuries.

2.2 Heat Stress

Humans and mammals in general, are homeotherms, meaning they internally regulate their core body temperature within a small range close to 37°C, even with a wide range of external environmental temperatures. It is important that the temperature of the cells in the human body stay close to this range and do not exceed 45°C so that the proteins are not denatured, or altered through temperature changes, and the cell does not die due to improper function of these proteins[12]. The outer shell of the body tends to be altered by the outside environment fairly easily while the inner core, which includes the vital organs in the head and the trunk, is more regulated within the small range discussed. Heat is transferred within the body through conduction from tissue to tissue and convection by flowing blood carrying the heat from the warmer tissues to the cooler tissues[12]. The production of heat from within the body occurs on a regular basis with metabolic activity. Even at rest, the body must use energy to perform basic bodily functions and to keep the body alive. When working, the amount of energy needed is increased and therefore the output of energy is increased partly in the form of work but mostly in the form of heat[13].

2.2.1 Thermoregulation

While the core body temperature is important for the proper function of the body, the skin temperature, along with the respiratory system, is important for heat exchange with the environment and thermoregulatory control through behavioral and physiological thermoregulation. The first type of thermoregulatory control, behavioral thermoregulation, involves thermal comfort[12]. Thermal comfort is influenced by both physiological and psychological factors. Within an ambient temperature range of 25.5-29°C, vasomotor control is the mechanism that either raises or lowers the skin temperature in order to maintain thermal comfort for the individual through the constriction and dilation of blood vessels. As the ambient temperature increases, heat loss through sweat evaporation must occur within the body to maintain a balance from the heat gain that occurs through the environment and metabolic heat. At the point where sweat evaporation can no longer take enough heat away from the body to maintain thermal equilibrium, the body continues to increase its temperature which is detrimental to the health of the individual[14]. Thermal equilibrium is maintained at a skin temperature of about 33°C (91.4°F). Thermal comfort according to ASHRAE is "the absence of unpleasant thermal sensations." Whenever there is a pleasant stimulus that can counteract any unpleasant sensation or if there are no sensations at all, the individual usually perceives themselves as comfortable[15]. A sensation of warmth or cold can be considered either comfortable or uncomfortable depending on whether it is adding to the physiological strain of the person or taking away from it[12]. The difference between heat stress and heat strain, according to the American Conference of Government Industrial Hygienists (ACGIH), is that heat stress is the "net heat load to which a worker may be exposed…" and heat strain is "the overall physiological response resulting from heat stress"[16]. In addition, within a small range around thermal equilibrium, usually determined by inter-individual factors, an environment that one may perceive as comfortable may be uncomfortable for someone else. Perceived comfort is more influenced by the psychological factors[14].

The physiological thermoregulation occurs through a graded control of heat production and heat loss. This means that as more heat needs to be released from the body to get towards equilibrium, different mechanisms, such as vasodilation or vasoconstriction, and secretion of sweat glands or shivering, work to release or produce heat in proportion to the amount that needs to be dissipated or maintained[12].

2.2.2 Heat Illness

If heat strain in an individual is not treated, it can lead to numerous heat illnesses[10]. Miliaria, also known as prickly heat or heat rash is caused when overheating causes the sweat ducts to be plugged leading to a rash. This tends to be more annoying than health threatening. Heat syncope, which is characterized by headaches, dizziness, and fainting, occurs in hot environments with prolonged standing[10]. Heat cramps, heat exhaustion, and heat stroke are progressive heat illnesses that stem from one another[6]. Heat cramps occur first, characterized by excessive sweating and involuntary muscle contraction of the voluntary muscles. When one is experiencing heat cramps, the body still is at a normal temperature. Heat exhaustion occurs next with a slight rise in core body temperature outside of the normal range. The individual could experience weakness, extreme fatigue, profuse sweating, fainting, headache, pallor, or an ashen color of the face, dyspnea, or shortness of breath, nausea, and/or vomiting[6]. Finally, heat stroke is considered a medical emergency in which all of the body's normal heat controls have failed. At this point, sweating stops and the skin feels hot and dry. The body temperature continues to rise and mental confusion, loss of consciousness, convulsions and even coma may occur[6], [10].

2.2.2.1 Fatigue: A Precursor to Heat Illness

Cognitive performance has been shown to be affected by heat stress and fatigue[17]. The occurrence of unsafe behavior increases in ambient temperatures that are no longer considered physiologically comfortable. Though the complexity of the task seems to have an effect on the degree of impairment, more simple tasks such as reaction time and mental transformation tasks are still important to consider in wildland firefighting. Specifically, multiple tasks being performed together can be affected by the presence of fatigue and heat stress[17]. This is important because wildland firefighters must often be focused on many different tasks as well as their surrounding when working in the field. In addition, cognitive performance is often more affected in long term exposures to stressful environments. The wildland firefighter has extremely long work periods so their ability to complete their tasks will likely be affected by their symptoms of heat stress[17].

2.2.3 A Comprehensive Measurement of Heat Stress: Physiological Strain Index (PSI)

The physiological strain index (PSI) is a measurement used to evaluate the effects of heat stress on the physiological response of a human through the use of the core temperature and the heart rate. The PSI is used in differing climates and with varying levels of exercise intensity. It can predict the heat strain even with little variability and slight changes in the parameters. The equation for PSI is:

$$PSI = (5 * (T_{ri} - T_{r0})/ (39.5 - T_{r0})) + (5 * (HR_i - HR_0) * (180-HR_0))$$

where: T_{ri}=current core temperature,

T_{r0} =core temperature at time 0,

HR_i =current heart rate, and

HR_0 =core temperature at time 0[18].

2.2.4 Heat Stress in Wildland Firefighting PPE

In the case of wildland firefighting, the environment sometimes tends to cause heat gain due to high surrounding temperatures. Heat may be gained through radiation from the sun or a nearby fire or through convection when the air temperature is higher than the skin temperature[19]. The heavy clothing that wildland firefighters must wear protects them from the buildup of body heat experienced in hot environments but also dampens the amount of heat that can be released through evaporation[12]. In addition, high levels of humidity that may be experienced in a wildland firefighting setting will also decrease the rate of evaporation[19]. The greater the weight and thickness of the clothing, the larger the impact will be[13]. The many avenues of heat gain lead to a short time frame that a wildland firefighter can work before experiencing symptoms of heat stress. Fitness and acclimatization have been recommended to increase the time that one wearing protective clothing can work; however these advantages are diminished as the clothing itself becomes more burdensome due to the decrease in evaporation[6], [12]. In addition to the clothing, extra equipment that must be carried by wildland firefighters which will not only add weight, but also inhibit air movement within the garment and further prevent the evaporation of sweat from the skin[12]. One example of this is the backpacks that trap air between the numerous straps.

2.3 Heat Transfer

The body must be able to liberate the heat that is built up from metabolic activity regardless of additional activity and the influence of environmental parameters. The ways that it can lose heat is through dry heat transfer, evaporative heat transfer, and respiration[13]. Through respiration, the body will lose about 10% of its heat through the lungs with the heating of inspired air if the environmental temperature is cooler than the temperature of the lungs. However, when the environment is hotter, heat will be gained through inspired air. In order for the body temperature to stay balanced, the amount of heat stored must be equal to zero. The balance is usually written as follows:

Store = heat production – heat loss = (metabolic rate – external work) – (conduction + radiation + convection + evaporation + respiration) [13].

If the heat production outweighs the heat loss then the body temperature will rise, and alternatively if more heat is lost than is being produced by the body, the body will cool down[13].

2.3.1 Dry Heat Transfer

The body transfers heat minimally through conduction. Conduction is heat transfer through touching of surrounding objects[13]. Since wildland firefighters are not touching objects in the environment very often, this type of heat transfer rarely comes into play outside of the conduction that occurs between the skin and the clothing they are wearing. There is a large amount of heat transfer that occurs through convection, or heat transfer through the movement of air along the skin. As air passes over the skin, it either dissipates some of the heat if the air is cooler or adds to the heat if the air is warmer than the skin[13]. Finally, radiation is heat transfer through the temperature differential of the skin and the surfaces of surrounding objects. This could be important depending on the environment, and particularly in wildland firefighting, it comes into play when the firefighters are working in the sun or near a fire as an avenue of heat gain. All of these forms of heat transfer in relation to clothing are often combined into a term called dry heat transfer[20]. Dry heat transfer is often expressed in W/m^2 and can be used to find the insulation value of the clothing in $m^2\,°C/W$

defined as the resistance to dry heat transfer (R_{ct}). The total insulation value includes all layers between the skin and the environment including the separate layers of fabric and the boundary air layers. These become important because still air is very insulative and accounts for over half of the usual clothing insulation[21]. As more layers of clothing are added, the added layers of fabric are not the only sources of insulation that need to be taken into account because there will be a boundary air layer in between. Clothing insulation is often expressed in units of clo which is equal to 0.1555 m^2 °C/W and is equivalent to the amount of insulation that would "balance the heat produced by a resting man under normal indoor climatic conditions" wearing a business suit along with the heat that is lost through evaporation and respiration[20].

2.3.2 Evaporative Heat Transfer

In the Sweat Evaporation Compensable zone, the use of evaporative heat transfer becomes important[14]. This is the point when the body must use sweat evaporation to cool down the body. The maximum amount of sweat that can be produced and sustained by the average human body is approximately 1L/hr [14]. The amount of evaporation (E_{req}) required to cool down an individual in this zone is equal to the metabolic heat production of the body plus or minus its heat exchange due to dry heat transfer and respiration. If the body cannot meet E_{req} due to water content in the air or impermeability of the clothing being worn, then the heat in the body will continue to build up[14]. The breathability of a garment determines how much sweat will be able to be evaporated off of the skin without interference. Breathability is usually described in terms of evaporative resistance (R_{et}) and is in units of kPa m^2/W[22]. In addition, the permeability index (i_m) is another way of describing the amount of evaporation that can occur through a garment. The permeability index ranges from 0 (totally impermeable) to 1(totally permeable) and is often used with the clo value and expressed as the Permeability index ratio (i_m/clo) [23]. This is a percentage that represents how much of the maximum possible evaporative cooling can be utilized for a garment in a particular environment[24].

2.3.3 Environmental Conditions in Relation to Heat Transfer

There are many environmental parameters that determine how much heat can be lost by the body through clothing. The temperature of the air is important relative to convective heat loss[13]. As the air runs over the skin, heat can either be lost from the body if the air is cooler than skin temperature, or gained if the air is hotter than skin temperature. If heat is being gained by the air, it can not only contribute to burns on the skin, but it also begins to push the body towards experiencing heat stress. The radiant temperature in the environment is the main contributor to burns on the skin in wildland firefighting[1]. This heat comes from the sun as well as fire at a distance. Firefighters are usually not required to work near enough to the flames to sustain burns convectively or conductively[1]. It is very common for the temperature of the sun and the surroundings to exceed the temperature of the skin so this is mostly a form of heat gain unless work is being done at night[13]. The most important surface temperature in heat exchange with the skin is the temperature of the clothing since the skin is fully covered with protective clothing and rarely is in direct contact with other objects. The temperature of the ground, equipment, and the temperature from the surrounding fire and sun has an impact on the temperature of the clothing. The fire and sun's temperatures also directly affect some unexposed areas of the individual's body such as their face and neck.

In addition to temperatures in the environment, the air's moisture concentration is very important when it comes to evaporative cooling[13]. The moisture in the air can either hinder, in high moisture concentrations, or encourage, in dry conditions, the evaporation of sweat into the environment. Since evaporation is the most important avenue for heat loss in wildland firefighting, moisture concentration is a very important factor in the development of heat stress. High moisture concentrations only allow the firefighters a short period of time before their body is overcome with heat stress[13]. The moisture concentration is often misinterpreted as the relative humidity. However, though they are closely related, the relative humidity is also dependent on temperature. As you raise the temperature of the environment, the same relative humidity would contain more moisture[13]. As long as the temperature of the air stays below the temperature of the skin, sweat would be able to evaporate even at 100% relative humidity.

The wind speed is also an important factor in heat loss through both convection and evaporation[13]. In environments when the temperature is cooler than the skin, the higher the wind speed, the faster the body is cooled down. However, in hot humid conditions, an increase in wind speed can lead to faster heat gain in the body. In order for this to occur, the weather conditions would have to include the right combination of high temperature and humidity for the convective heat exchange to outweigh the potential evaporation benefit.

2.3.4 Clothing Properties in Relation to Heat Transfer

All of the contributors to heat stress combine to determine how much heat exchange will occur between the body and the environment[13]. However, when you add clothing to the equation, there is an additional barrier hindering this heat exchange. This barrier not only includes the clothing itself but also the still air that is trapped underneath. Air is a very effective insulator so the amount of heat that is trapped by the clothing can never be accurately predicted without accounting for the effect of the still air layer[13]. The effects of clothing on heat transfer can be represented by the following equations:

$$Dry\ Heat\ Loss = \frac{(t_{sk} - t_a)}{I_T}$$

where: t_{sk} = skin temperature, t_a = air temperature, and I_T = clothing insulation, including air layers[13].

$$Evaporative\ Heat\ Loss = \frac{(p_{sk} - p_a)}{R_T}$$

where: p_{sk} = skin vapor pressure, p_a = air vapor pressure, and R_T = clothing vapor resistance, including air layers[13].

These equations confirm the importance of the environmental parameters. When the air temperature is greater than the skin temperature, a negative heat loss, or heat gain can occur[13]. Similarly, when the air vapor pressure is greater than the skin vapor pressure, or the moisture concentration of the air is higher than the moisture concentration on the skin, no loss of heat through evaporation occurs, and heat stress is possible.

The microclimate of the still air underneath the clothing is strongly affected by the thermal properties of the clothing being worn[19]. If the sweat from the skin cannot evaporate at a fast enough rate, the water vapor pressure and the relative humidity continues to rise causing an increase in the microclimate air temperature and therefore the skin temperature. It is therefore important to have ventilation throughout the clothing. This can often be achieved by movement through walking and other tasks performed during wildland firefighting[19]. However, if heat being produced by the movement outweighs the benefit of the ventilation then heat will still build up in the microclimate. Ventilation to the outside air is more beneficial than ventilation through the movement of air in the microclimate if the surrounding air in the environment is cooler. This allows for the exchange of hot air for cool air allowing more heat to be dissipated.

2.4 Combating Heat Stress

The environmental conditions, specific characteristics of the individual wildland firefighter, operational factors or the tasks that they must complete, and personal protective equipment all contribute to the buildup of heat stress[12]. Because the environment can rarely be manipulated, the other factors must receive the focus. Those who are involved with the training and the medical clearance of the wildland firefighters must make sure that neither their tasks nor their individual health are over-contributing to the buildup of heat stress. In addition, the individual wildland firefighters must maintain fitness, monitor their substance (alcohol and caffeine) intake, and make sure to monitor any symptoms they are having of heat stress on the job. Hydration and how much they are resting during their work periods are also important factors to be taken into account when trying to minimize heat stress. It is the responsibility of those designing and regulating the personal protective equipment to reduce the buildup of heat stress from clothing.

2.4.1 NFPA 1977 Standard

NFPA 1977: Standard on Protective Clothing and Equipment for Wildland Fire Fighting is the official standard for regulating the design and protection levels of PPE in wildland firefighting. The NFPA began work on this standard in April 1989 when requests were made for a separate standard made specifically for wildland firefighting[25]. The Wildland Fire Fighting Protective Clothing and Equipment subcommittee of the NFPA was formed to develop this standard. Through their research, they discovered that a majority of the injuries in wildland firefighting came from heat stress and not a lack of protection from burns. Because of this, their main focus became to "provide thermal protection for the wildland fire fighter against external heat sources with flame-resistant clothing and equipment while not inducing and extraordinary internal heat stress load"[25]. The first issue was effective August 20, 1993. The original committee set the value for total heat loss (THL), a parameter to measure heat stress, at 450 W/m^2 seemingly because it was a value that all of the garments that were currently being used could pass, but there is no experimental basis to confirm that this value should be used mentioned within the relevant NFPA documents[25]. There was a proposal to increase the original value 450 to 550 W/m^2 in 2004 but it was rejected by the committee due to a lack of experimental reasoning to change it[26]. The 2011 edition, the most recent, includes a table that puts a limit on the total surface area of reinforcements allowed on wildland firefighter garments in order to avoid the buildup of double layers and therefore heat stress. Reinforcements are any layers of material that are added to the garment such as pockets, knee pads and elbow pads, and trim that may affect how much heat could pass through the garment. Only the base composite is normally measured and previously there was no restriction on the type or amount of reinforcements. In the current standard the amount is restricted. However, the area that the reinforcements are allowed to occupy is still a large area and the type is not restricted so it, in theory, could be fully covered in heavy, impermeable materials. A copy of the table is included in Appendix A[25].

2.4.2 Clothing Complaints from the Wildland Firefighter

In order for a garment design to be successful it has to provide adequate protection while allowing heat to be released to avoid heat stress. It must allow the wildland firefighter mobility to do their job and be accepted by firefighters. Firefighters must accept their gear because they are the ones that are in control of how much the garment will be used. It does not matter how useful the garment is if the wildland firefighters that are supposed to be using it are not willing to wear them. The comfort of wildland firefighters in their gear could affect how efficiently and accurately they can perform the tasks. If they are concerned with problems that they are having with their garments while they are supposed to be fighting wildland fires, they could be distracted leading to incorrectly completed or omitted tasks, or worse, injury or death. Specifically, when trying to find out if heat stress or protection is more important to firefighters, actually speaking to those firefighters who have worn the garments and seen their effects are important. It is difficult to get a consensus on the opinions of the wildland firefighters; however some blogs show discussions of layering in relation to the balance of heat stress and protection. Within this discussion some firefighters feel that protection is more important. One on WildlandFire.com said:

"Which issue is more critical, thermal protection, or heat retention? Talk to any survivor of a burn injury, and the treatment is horrific, heat related injury is usually treated with cooling measures and fluids, not surgery and skin grafts, and burn scars for life"[27].

At the same time, others feel that heat stress is a more important factor. One firefighter in the same blog states that:

"if we needed to be more safe in the direct attack environment, and burn prevention was the only factor, we would fight fire in turnouts. We have to have a balance somewhere between turnouts and station uniforms. Fatigue, productivity and heat injury have to be part of the equation. We transport many people off of our fires for heat and dehydration. I think that if people find themselves in catastrophic firestorms than even turnouts wouldn't be effective. The last thing is how many near misses or burns include inability to egress due to weight and fatigue, that's why we toss our tools. If you are to fatigued to remove yourself from danger quickly it rarely matters what you are wearing"[27].

It seems as if the firefighters are dealing with such extreme conditions, that their survival is more of a priority than not being uncomfortable. However, their comfort is also affecting their survival and therefore is an important aspect of the garment.

In a personal interview, David Moore, a fire chief in Glendale, OH and a wildland firefighter in the United States Forest Service (USFS) states that more verbal complaints come from structural firefighters fighting wildland fires than from wildland firefighters[28]. Structural firefighters would likely be wearing their gear as opposed to wildland firefighter gear because this is what they are used to have easiest access to. Moore states that for wildland firefighters who use the uniforms that are currently provided, the changes that they would like to be made to the uniform are lighter weight material, faster moisture wicking, and more durability. David Moore wears Kevlar® pants because they are more rugged than the Nomex® pants but most firefighters who cannot afford to buy their own uniform wear what they are provided with[28]. The fit can become important when it comes to ventilation and protection issues. Overall, the consensus was that loose clothing was better in the environment because it provided better ventilation. In terms of heat stress, Moore states that it is more important than comfort because it is life threatening; however since problems with thermal comfort occur more often it would be considered the bigger complaint. Therefore, both heat stress and thermal comfort are important aspects to be studied. He made it clear that gear makes a difference in the wildland firefighting atmosphere but not because of protection. According to Moore, "way more deaths from overexertion and heat stress occur than burning and more protection would probably not save the people who died from burning"[28].

There is a common misconception that the only thing that matters within the garment is how much it protects the individual from getting burns. The culture in wildland firefighting indicates that if they complain about being uncomfortable or heat stress of a garment that it may show weakness. Because of this mentality, there have been a few reported cases of heat stress or dehydration within wildland firefighting. Figure 2.1 shows these cases specifically in the Interagency Hot Shot Crew (IHC), the wildland firefighting agency that Mann who died in 2011 was a part of[7]. According to NIOSH, many cases of heat illness are experienced by workers but are not reported because it is a “part of the job” and the firefighters want to be rehired. In addition, firefighters and the committees setting the standards also fail to realize that the comfort of the firefighter will affect their cognitive skills and their ability to complete their tasks[29].

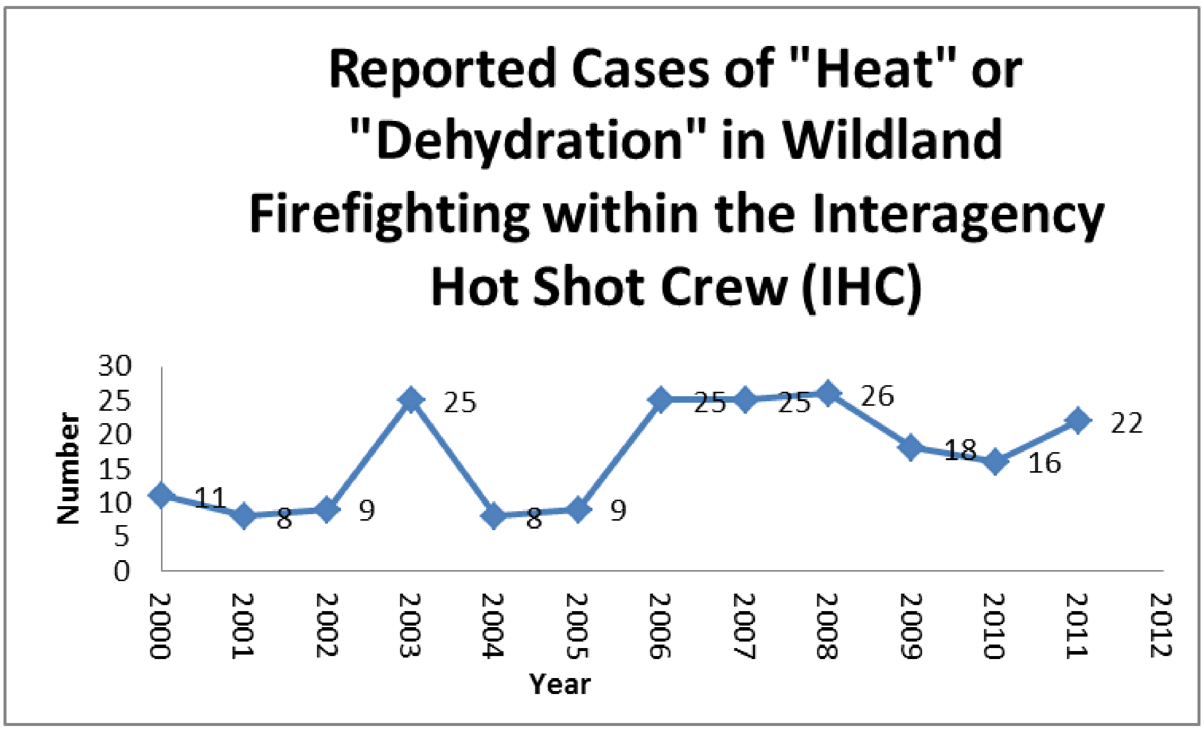

Figure 2.1: Reported Cases of Heat Stress in Wildland Firefighting within the Interagency Hot Shot Crew (IHC) [7]

2.5 The Wildland Firefighter's Environment

The environment that a wildland firefighter will encounter on any given day is never a predictable one. There is a large range of conditions that are considered suitable for a naturally occurring fire. The only requirements necessary are that climate have enough moisture to allow vegetation to grow in order to create fuel, a dry season to create burning conditions, and some source of ignition whether it be extremely hot weather, lightning, or other causes[30]. The type of fuel available is also important since dryer, fluffier brush with a lot of air spaces tend to ignite better than thick moist fuels. The weather specifically controls the drying of the fuels and plays a role in how the fire will behave after it is ignited. In addition to low moisture in the fuel, warm dry air, and high winds produce the most intense fires[30]. These fires spread fast and are the hardest for wildland firefighters to put out.

2.5.1 A Typical Work Day

Most wildland firefighters are seasonal workers. They are hired during the months that it is most likely a wildfire will start. These firefighters are hired by the U.S. government or state agencies across the country. During a typical day when there is an actual fire, a wildland firefighter is hiking, building firelines, removing brush, doing chainsaw work, and setting backfires[9], [31–33]. The activity level associated with this work is about 6.1 METS[34]. The MET, the standard metabolic equivalent, is a unit that estimates how much oxygen the body is using during activity[35]. One MET is equivalent to the oxygen consumed by the body at rest. Activity above 6 METS is usually considered vigorous-intensity physical activity. Self-pacing is important when it comes to controlling over-exertion so wildland firefighters are encouraged to work at a pace that they are comfortable with. For an unfit worker, it would take more energy to do a specific task than it would take a fit worker. Therefore, fit workers tend to get more work accomplished with less fatigue.

A wildland firefighter's work day usually lasts between 12-18 hours; however, some wildland firefighters work up to 24 hours in a day with no sleep[32]. The estimated work: rest ratio of a typical wildland fire can vary greatly according to different studies. Some will claim that the ratio is 1:2 or 3:1 but the studies that look at fires in the US lean more toward a 2:1 ratio[9][31][32]. These are important parameters in wildland firefighting because active time with inadequate rest can lead to fatigue. This then leads to the incompletion of tasks and a slow reaction time, which can lead to burnovers. Natural fires usually last anywhere from 34.6 minutes to 434.6 minutes[31]. The time to suppress experimental fires generally takes anywhere between 45 minutes and 129 minutes[9]. On the days when there are no fires, which encompass most of the season, firefighters spend their days doing organized physical training and project work[36]. Some of the project work includes forest thinning or performing other hazard reduction or fire prevention activities.

2.5.2 Wildland Firefighting Garments

There are two types of gear predominantly worn in the United States: double layer uniforms (Figure 2.2) worn by Cal-Fire and other agencies in southern California, and single layer uniforms (Figure 2.3) worn by the United States Forest Service (USFS) [37][38]. The Cal-Fire double layer uniform consists of a helmet, goggles, radio, fire retardant Nomex®

jacket with retroflective strips at the waist and wrists, equipment web belt, single-layer gloves, emergency shelter in a pouch, overpants, leather boots, accessory pack, hose clamp, and a canteen/water bottle[39]. This is all worn over a station uniform that consist of a cotton, short or long sleeved, t-shirt and Nomex® station pants[37].

Figure 2.2: Double Layer Cal Fire Ensemble

Figure 2.3: Single Layer USFS Ensemble

The single layer uniform consists of a Nomex® fire shirt with a 100% cotton t-shirt underneath, Nomex® fire pants with 100% cotton undergarments underneath, boots, a line pack, head lamp, helmet, goggles, radio, bladder bag, gloves, shovel, Pulaski, brush coat, chain saw, and a drip torch[38]. The clothing is important because it provides protection from radiant exposures for long periods of time. The clothing also provides a reasonable amount of protection time to allow the firefighters to move out of the convective or conductive heat conditions. However, they are not expected to perform in these conditions. Too much protection can lead to heat stress which is often being seen in the double layer uniforms[1].

2.5.3 Wildland Fire Weather Conditions

The temperatures reported for wildland fires range drastically. The temperature is important to help keep the fuels dry so they are able to ignite[30]. Thinner fuels especially respond quickly to temperature changes. In addition, the temperature strongly influences how the fire spreads after it is ignited. In "unstable air" or air where the temperature gradient is steep with the ground being much warmer than a little higher up, vertical movement is encouraged[30]. This vertical movement leads to fierce burning in addition to strong gusts of winds swooping into the forest ground. Project Aquarius 6, done in Australia, and the study done in Spain both report ambient air temperatures between 20 and 30°C[9][31]. However, a study that looked at conditions in the US reported temperatures between 35°C and 45°C. In relation to heat stress, high temperatures can limit cooling and/or raise the body temperature of the individual depending on the temperature differential between the skin and the ambient temperature. There is a difference between the ambient temperature and the temperature of the surroundings, such as the radiant exposure. The ambient temperature is the actual temperature and humidity of the air, while the temperature of the surroundings can make the temperature of the body feel different than what would be felt by the air without it. Radiant sources such as the sun or a fire would be examples of surroundings within an environment that would perform this way. Project Aquarius 6 reported the radiant load to be 18.0±10.5°C[9]. The radiant load caused by the fire is important in determining how much protection is needed from the garment. It is important that the protection provided doesn't exceed what is needed due to the threat of heat stress. However, if the garment is not protective enough the firefighter will sustain burns and the radiant heat will also raise the body temperature of the individual. The radiant load can also raise the temperature that is felt by the body even though it may not raise the actual ambient temperature.

The humidity in a typical wildland environment also ranges widely. Project Aquarius reported the average relative humidity to be about 47% but also stated that it could be as low as 14% or as high as 81%[9]. Another study entitled, "Awake, smoky, and hot" determined the relative humidity in wildland fires to be less than 20%[33].A high relative humidity will limit sweat evaporation and therefore heat loss so it is important to know this parameter when studying the effects of the garments on the wildland firefighters. In addition, with the fire, the humidity determines how slow the fire will burn. The more damp the air, the slower the fire will burn and the slower the shrubbery in its path will dry up and become an effective fuel source. Therefore, a lower humidity is more beneficial for the firefighter's well-being and but negatively affects the task of taming of the wildland fire.

Finally, there is a large range of wind speeds reported in wildland firefighting. The wind speed can dictate how fast the fire will spread in wind driven fires[30]. These are the fires in which horizontal wind is powerful enough to prevent or break up a convection column. Project Aquarius 6 reported low wind speeds ranging from .7 to 1.5 m/s[9]. Other studies, such as "'Awake, smoky, and hot': Providing an evidence-base for managing the risks associated with occupational stressors encountered by wildland firefighters," reported high wind speeds ranging from 6.94 to 20.83 m/s[33]. It is important to pinpoint what the wind speeds are near the fire front as well as away from the fire front because faster winds lead to faster evaporation of sweat. In addition to this mechanism of heat loss, cooling can occur by convection if winds are cool enough. However, the wind speed can add to heat stress if the winds are hotter than skin temperature.

2.6 Traditional Measurement of Heat Stress

The NFPA 1971 standard calls for the measurement of heat stress in structural firefighting in 1989 through the total heat loss test[40]. This uses the sweating guarded hot plate to take measurements on a fabric level. Manikins were also considered for this test but due to its limited availability in the industry and the high cost compared to the hot plate, that idea was rejected[40]. Outside of NFPA standards the sweating manikin is still used to give a more accurate depiction of heat exchange between the person and the environment, taking into account air layers produced on the garment level and double layers from the clothing itself including reinforcements.

2.6.1 Total Heat Loss on the Sweating Hot Plate

The committee put together to develop the Total Heat Loss test, identified one test for thermal insulation measurements and three tests for evaporative transfer measurement when first asked to review literature and the availability of test apparatuses[40]. The guarded hot plate and the sweating guarded hot plate were selected as the final test apparatuses because they could measure layered ensembles and they were compatible with the thermal balance theory. According to NFPA 1977, the samples must be laundered five times as specified elsewhere and conditioned at 25°C ± 7°C and a relative humidity of 65% ± 5% for at least 4 hours[25]. A minimum of 3 specimens must be tested per garment type 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. From this testing, the average intrinsic thermal resistance (R_{cf}), the average apparent intrinsic evaporative resistance (AR_{ef}), and the average total heat loss (Q_t) are reported.

2.6.1.1 ASTM F-1868 Standard

This standard calls for the use of a guarded sweating hot plate, used either dry or sweating, for both the thermal and evaporative resistances[41]. Along with NFPA 1977, the standard sets most of the specifications within the testing apparatus and procedure required for the garment to be certified. However, some specifications are not too specific and allow leeway among the test facilities. It is required that the garments be certified by a third party whose testing facility has been approved[41]. NCSU has a specific setup that is operated in accordance with testing facilities that regularly perform garment certifications though actual garments are not certified here. The methods described will reflect this specific setup.

2.6.1.2 Measuring Thermal Resistance

In order to measure the thermal resistance (R_{ct}) on the fabric level the sample must be cut to 20” by 20” in order to fit the dimensions of the outer plate[42]. The sample is then placed flat on the plate where the inner heater and plate assembly are heated to 35°C to mimic a human’s skin temperature. The fabric is always placed in direct contact with the plate, and in the case of multiple layers, the outermost layer is laid on top towards the ambient environment. Two heaters within the system ensure that all heat generated by the main heater is directed toward the sample[43]. A 5” guard heater surrounds the main inner heater and stops lateral heat flow to and from that heater and a second bucking heater is located below the main heater to ensure that no axial heat is kept at 25°C and 65% RH[42]. Using several fans, also in the environmental chamber, the wind speed above the sample is maintained at 1 m/s. The amount of electrical power used to keep the plate at a constant temperature under those conditions is then measured by a computer. That value is proportional to the amount of heat that is lost through the fabric[42].

2.6.1.3 Measuring Evaporative Resistance

To measure evaporative resistance (R_{et}) most of the same parameters used in the measurement of thermal resistance are used except that there is water being fed to the porous plate[42]. A cellophane membrane is laid on top of the plate to prevent the water from wetting the fabric while still allowing water vapor to evaporate through the fabric. The computer then uses the thermal resistance of the fabric as measured before to calculate the new power requirement in relation to the amount of water evaporating per unit time and the latent heat of vaporization. Since it uses non-isothermal conditions there may be some condensation so the evaporative resistance is deemed the apparent evaporative resistance (AR_{et}) [42]. Using AR_{et}, R_{ct}, and bare plate resistance measurements, the THL value, in W/m^2, that NFPA 1977 calls for can be calculated.

2.6.1.4 Calculations

The thermal resistance (R_{ct}) is calculated using the measurements of surface temperature, test chamber air temperature, input power to the main heater, and the area for the test samples using the following equation:

$R_{ct} = \frac{(T_s - T_a)A}{H_c}$, 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 (°C),

T_a = air temperature (°C), and

H_c = power input (W) [41], [43].

The evaporative resistance is calculated using the R_{ct} along with the input power to the main heater when the porous 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 area of the test samples in the following equation:

$AR_{et} = \frac{(P_s - P_a)A}{H_T - (T_s - T_a)A/R_{ct}}$, where: AR_{et} = apparent total evaporative resistance of the specimen and surface air layer ($kPa \cdot m^2/W$),

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 (m^2),

H_T = power input (W),

T_s = temperature at the test plate surface (°C),

T_a = temperature in the air flowing over the specimen (°C), and

R_{ct} = total thermal resistance of the specimen and surface air layer (K·m^2/W) [41].

Finally, the THL value of a fabric must be calculated. In order to do this, the thermal resistance of the sample alone (R_{cf}) and the intrinsic evaporative resistance of the sample alone (AR_{ef}) must be determined. The R_{cf} is calculated by subtracting the average bare plate resistance (R_{cbp}) from the average total thermal resistance (R_{ct}) of the samples tested. The AR_{ef} is calculated by subtracting the average bare plate evaporative resistance (R_{ebp}) from the average apparent total evaporative resistance (AR_{et}) of the samples. Then the THL can be calculated using the following equation:

$$Q_t = \frac{T_s - T_a}{R_{cf} + K_c} + \frac{P_s - P_a}{AR_{ef} + K_e}$$

$$= \frac{10.0°C}{R_{cf}+0.04} + \frac{3.57kPa}{AR_{ef}+.0035}$$, where: Q_t or THL = total heat loss (W/m^2),

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

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

T_s = temperature at the test plate surface (°C),

T_a = temperature in the air flowing over the specimen (°C),

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[40], [41].

In addition, the thermal and apparent evaporative resistances can be 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 ($K \cdot m^2/W$)

$i_m = \left(\frac{R_{ct}}{AR_{et}}\right) * 0.061$, where: R_{ct} = thermal resistance ($K \cdot m^2/W$), and

AR_{et} = apparent evaporative resistance ($kPa \cdot m^2/W$)[44].

2.6.2 Total Heat Loss on the Sweating Manikin

The sweating hot plate is useful for measuring heat loss on the fabric level. However, the sweating hot plate does have some limitations[42]. In reference to the values given from the sweating hot plate, they can only be provided for the fabric and not the clothing that wildland firefighters would be wearing[42]. The sweating hot plate is unable to take into account 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. In addition, the reinforcements on the clothing, though there is a part of NFPA 1977 that addresses those, are not fully taken into account. Finally, heat loss through convection in ventilation and body motion is not taken into account. The sweating manikin is able to address all of these issues. The sweating manikin at NCSU is a Newton model manikin from Measurement Technology Northwest (MTNW) and has 34 separately controlled heated sections with pores built in for sweating, shown in Figure 2.4[45]. Additionally, there is a fluid heater inside the manikin to ensure that the water coming through the pores maintains the set temperature. The heaters that control each of the zones maintain the manikin temperature setpoint and also contain wire sensors to measure the individual temperatures. The manikin is connected to a computer program that is able to control the flow and temperature setpoints for each section.

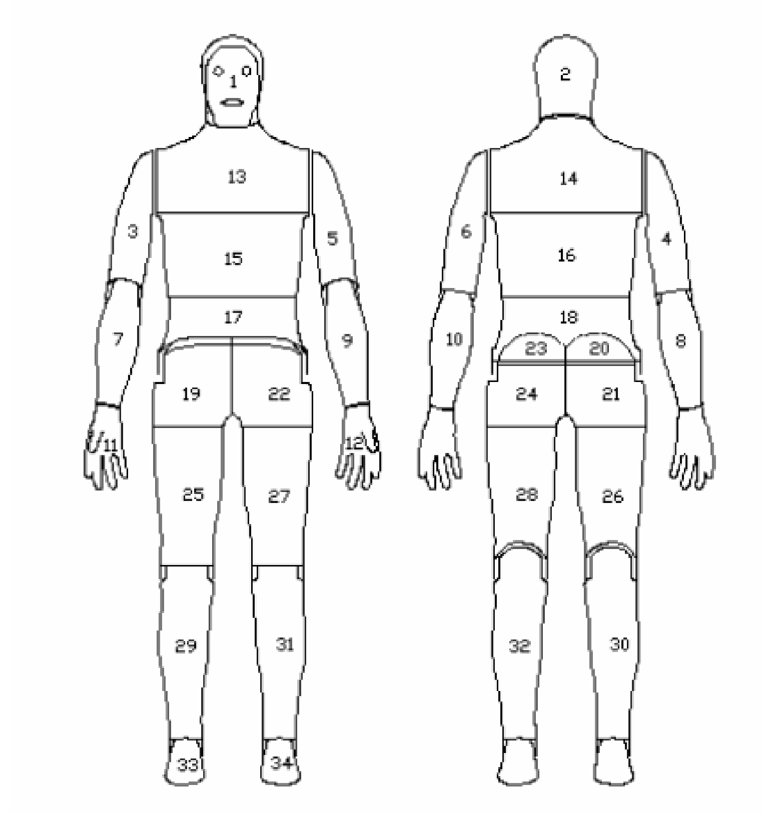

Figure 2.4: Newton Zone Detail[45]

2.6.2.1 ASTM F-1291 Standard

The ASTM F1291-10: Standard Test Method for Measuring the Thermal Insulation of Clothing Using a Heated Manikin determines the dry insulation values of clothing ensembles in a calm, cool environment[46]. It requires that the manikin being tested have a total surface area of $1.8 \pm 0.3\text{m}^2$ and a height of 170 ± 10 cm to ensure that it will fit a standard garment size. The surface temperature must be set at 35°C with local deviations no more than ± 0.3°C. A standard set of test conditions are given for the test to be valid[46]. The air temperature must be at least 12°C lower than the manikin's mean temperature (23°C) during the test. The air velocity must be 0.4 ± 0.1 m/s and the relative humidity must be set between 30% and 70%, preferably 50%. The testing for this study used a 1 m/s wind speed to match the sweating hot plate standard for a better comparison. Three replications of each garment must be done by either testing three separate replicates or removing the same replicate and redressing the manikin to ensure normal variations in dressing and instrumentation are taken into account. In the beginning of each series of clothing tests on the manikin, a nude test must be done to measure the insulation of the air layer surrounding the nude manikin (R_a) [46].

2.6.2.2 ASTM F- 2370 Standard

The ASTM F2370-10: Standard Test Method for Measuring the Evaporative Resistance of Clothing Using a Sweating Manikin sets the specifications for determining the evaporative resistance of clothing on a static manikin test in a relatively calm environment[47]. The manikin size specifications are the same that are required in ASTM F1291. However, there is an additional requirement that the manikin must have the ability to evaporate water from its surface. This can be through the use of a fabric skin or a valve delivery system in the manikin. The entire surface of the manikin must be heated and sweating at all times throughout the test[47]. The manikin temperature is kept the same as ASTM F1291 as well (35°C). For an isothermal test, the environment must be kept at isothermal conditions. The air temperature must be kept the same as the manikin to ensure that there is no dry heat transfer[47]. The air velocity is kept the same as the dry test, however the relative humidity must be 40 ± 5% throughout the test[47]. A nude test for the evaporative resistance provided by the air layer around the nude manikin (R_{ea}) must also be conducted at the beginning of each series of clothing tests.

2.6.2.3 Calculations

The total thermal resistance of the clothing system including the air layer resistance (R_t) can be calculated by using the area of the manikin, the temperature of the manikin, the air temperature, and the power required to heat the manikin along with the following equation:

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

R_t = total thermal resistance (insulation) of the clothing ensemble and surface air layer (°C·m^2/W),

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

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

T_a = temperature in the air flowing over the clothing (°C), and

H = power required to heat manikin (W) [46].

To determine the average intrinsic insulation value of the clothing alone (R_{cl}), the total thermal resistance for of the clothing ensemble and surface air layer, the thermal resistance of the air layer measured during the nude test, and the clothing area factor found in Table 1 of ASTM F1291 or ISO 9920 can be used in the following equation:

$R_{cl} = R_t - \frac{R_a}{f_{cl}}$, where:

R_{cl} = intrinsic clothing insulation (°C·m^2/W),

R_t = total thermal resistance (insulation) of the clothing ensemble and surface air layer (°C·m^2/W),

R_a = thermal resistance of the air layer on the surface of the nude manikin (°C·m^2/W),

f_{cl} = clothing area factor (dimensionless) [46].

The R_{cl} can then be converted to I_{cl} by multiplying the R_{cl} by 6.45.

Finally, the parallel method of calculating the total evaporative resistance will be used where the area-weighted temperatures of all the sweating body segments are summed and averaged, the power levels to all body segments are summed, and the areas are summed before the total resistance is calculated using the following equation:

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

R_{et} = total evaporative resistance of the clothing ensemble and surface air layer (kPa·m^2/W),

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

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

A = area of the manikin's surface that is sweating (m^2),

H_e = power required for sweating areas (W),

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

T_a = temperature in the air flowing over the clothing (°C), and

R_t = total thermal resistance (insulation) of the clothing ensemble and surface air layer (°C·m^2/W) [47].

To determine the average intrinsic evaporative resistance of the ensemble alone (R_{ecl}), use the mean R_{et} value and the following equation:

$R_{ecl} = R_{et} - \frac{R_{ea}}{f_{cl}}$, where:

R_{ecl} = intrinsic evaporative resistance of the clothing ensemble (kPa·m^2/W),

R_{et} = total evaporative resistance of the clothing ensemble and surface air layer (kPa·m^2/W),

R_{ea} = evaporative resistance of the air layer on the surface of the nude manikin's sweating surface (kPa·m^2/W), and

f_{cl} = clothing area factor (dimensionless) [47].

The predicted heat loss for a 25°C and 65% relative humidity environment can be calculated based off of the thermal and evaporative resistance (R_t and R_{et}) measurements taken from the sweating manikin using the following equation:

$$Q_{t(predicted,T,RH)} = \frac{(T_s - T_a)}{R_t} + \frac{(P_s - P_a)}{R_{et}}$$

, where: $Q_{t(predicted,T,RH)}$ = predicted manikin THL for specified environmental conditions (W/m^2), T = specified temperature condition (°C),

RH = specified relative humidity (%),

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

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

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

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

R_t = intrinsic thermal resistance of the test ensemble and surface air layer ($K \cdot m^2/W$), and

R_{et} = total evaporative resistance of the test ensemble and surface air layer ($kPa \cdot m^2/W$)[48].

This predicted total heat loss ($Q_{t(predicted,T,RH)}$) will be referred to as the manikin THL throughout the study.

2.6.3 Physiological Human Testing

Physiological Wear Tests use a specific group of test subjects chosen to best be able to replicate conditions seen in the end use application of the clothing[49]. Participants are instrumented using VitalSense software to collect data on their heart rate, skin temperature, and core temperature while completing the protocol. Subjective responses on the garments are also collected and less traditional measurements of reaction time to measure cognitive performance are taken. This physiological wear trials loosely followed ASTM F 2668: Standard Practice for Determining the Physiological Responses of the Wearer to Protective Clothing Ensembles and are approved through the Institutional Review Board for the Protection of Human Subjects in Research (IRB) at NCSU and FEMA[49]. In the human physiological testing aspect of the study, it is important to show differences between the garments if they exist. Environmental conditions must be within a range where the subjects are working hard enough to elicit differences in the physiological response to different garments but not so hard that all of the garments give the same results. This may be a small range but it is important that the study uses those parameters. In addition to being within this range, it is important that the parameters are representative of wildland conditions. It is important that the study is like a typical environment that the wildland firefighters would be using the garment in to show an accurate portrayal of how the garment would perform in the field, establish relevance, and make the study relatable to the user community. It is difficult to define conditions that will meet both criteria. However, numerous studies have been performed to determine the typical conditions of a wildland fire as well as some that have been done on actual wildland garments.

2.6.3.1 Previously conducted Wildland Physiological Studies

Four wildland firefighter test protocols were examined in this research for the analysis of wildland firefighting gear. The first, “Project Aquarius 13: The thermal burden of high insulation and encapsulation in wildland firefighters’ clothing” was conducted in

Australia and compared the “heavy clothing” and “light clothing” options worn by their firefighters. This study found that increasing protection leads to thermal burden that outweighs the benefits. Specifically, it found that the light clothing performed the best, sweat was mostly absorbed by the undergarments, and that the heavy clothing restricted the evaporation of sweat and therefore the dissipation of heat[2]. The next study entitled “Wildland Fire Uniform Configurations on Physiological Measures of Exercise-Heat Stress” was part of a larger study that investigated the health and safety of wildland firefighters in the field. This study was conducted by the University of Montana compared three popular wildland firefighting uniform configurations used in the US based on their effects on physiological indicators of heat stress. It found differences in these garments, concluding that the double layered uniform performed the worst in terms of thermal comfort[50]. At Auburn University, another study entitled “The Development of Prototype Wildland Firefighter Protective Clothing” was done. It compared a current garment design and material used in the field to a new garment design and composite material based on protection and their effects on physiological indicators of heat stress. The study concluded that the composite material did not significantly increase core and skin temperatures, the new design had greater range of motion, and the current fabric was preferred for comfort[51]. Finally, The Work Capacity Test ensures that the firefighters who will be working in the field have the amount of fitness necessary to perform these tasks without excessive difficulty[52].

When considering these studies, it is important to note that the University of Montana study used a protocol that showed differences in the garments. This is a necessary requirement for the protocol that will be used in this project. However, it must be noted that there was no comparison in protection within this study[50]. Also, it is important to realize that the objective of the Auburn study was to show that the new material and design did not add additional thermal burden to the wearer, though it added protection. Finally, the Work Capacity Test is not conducted in a laboratory setting and does not have controlled conditions. In fact, it is important that the subjects are in ideal conditions when the test is being conducted. Therefore, this may not be a realistic environment to compare to wildland firefighting[52].

2.6.3.1.1 Activity Characteristics

In Project Aquarius, the overall time of the study was 120 minutes: 60 minutes with subjects sitting in a warm chamber (with the subjects coveralls partially opened) followed by 60 minutes of the subject stepping on and off of a 30 cm stool. The activity level of this work was about 12 steps per minute which equated to between 4.292 and 5.214 METS[2]. The University of Montana study took 180 minutes to complete. This included 150 minutes of activity which consisted of treadmill walking at 3 mph and 4% grade and 10 minutes of rest per hour in the heat chamber with the pack removed in which they could drink water as needed out of premeasured bottles. The activity was 6.143 METS based on ACSM equations[50]. The Auburn study, took 120 minutes to complete with 117 minutes of treadmill walking at 3.5 mph and a graded altered to reach a 6.57 METS work rate using the VO_2 method. Only 1 minute of rest was provided every 30 minutes during which the subject could drink up to 300 mL of water[51]. Finally, the Work Capacity Test consists of a 3 mile quick hiking test that the subjects must complete within 45 minutes. It is recommended that they drink 1-2 cups of water before the beginning of the test and they are allowed to carry a water bottle with them throughout the test[52].

2.6.3.1.2 Gear

For Project Aquarius, the subjects wore either “light clothing” or “heavy clothing.” The light clothing consisted of cotton coveralls, a cotton t-shirt, and cotton briefs. The heavy clothing consisted of 100% wool-knitted long johns and a long-sleeve polo neck vest, as well as a wool twill coverall treated with flame retardant. Both sets of subjects also had to wear boots, a helmet, an axe belt, and goggles. This study also included structural firefighting turnout gear[2]. The University of Montana study had three different uniform configurations. The first was the standard Forest Service issue which included Nomex® pants and shirt. The second was a Kevlar®- Nomex® blend pant with a standard Forest Service issue shirt. The final configuration was the Cal-fire double layer uniform made of Nomex®. With all configurations, the subjects also wore gloves, a hard hat, a cotton t-shirt, athletic shoes, and a 20 kg fire pack[50]. In the Auburn study, the subjects wore a “current design constructed from present material, [a] current design constructed from new composite material, [a] new design constructed from present material, [and] new design constructed from new composite material”[51]. In addition they also wore a cotton/polyester t-shirt and underwear[51]. Finally, in the Work Capacity test there are no specific requirements in the clothing. For shoes however, they must be ankle supported for the Pack and Field tests and they must carry a 45 lb. pack[52].

2.6.3.1.3 Environmental Characteristics

In Project Aquarius 13, the parameters used were 30°C with no added radiant heat, 33% relative humidity, and an air velocity of 0.5 m/s in no specified direction[2]. In the University of Montana study, the environmental parameters were 37°C ± 0.05°C and 30 ± 7.6% RH with no radiant heat load and no wind[50]. The study done at Auburn University had an environment with a temperature of approximately 32°C, 45-55% RH, an air flow of approximately 5 mph toward the face of the subject using a fan, and a side radiant heat load of .025 cal/cm^2/sec. Specifically, "the radiant heat load was achieved by placing three 250 W heat lamps each on two vertical rows eighteen inches away from the shoulder of the subject"[51]. The lamps were not used the whole time and rather were turned on and off every 30 minutes starting at the beginning of the trial[51]. Finally, the Work Capacity Test simply recommend a day with low wind and a moderate temperature and humidity to reduce the possibility of heat stress[52].

2.6.3.1.4 Measurements

Project Aquarius measured the rectal core body temperature, skin temperature at 6 sites, the heart rate, oxygen consumption, and sweat loss of the individuals. They also measured the sub-clothing air temperature, or microclimate, over the chest and back and did a subjective rating of thermal discomfort, sweatiness, and perceived strain[2]. The University of Montana study measured the skin and core temperature and the heart rate and also did a subjective rating of thermal comfort and perceived exertion[50]. The Auburn study investigated the body weight of the individual with and without the ensembles, VO_2, heart rate, rectal and skin temperature, and a subjective rating of perceived exertion[51].

2.6.4 Non-Traditional Measurements of Clothing Related Heat Stress

2.6.4.1 Physiological Manikin Testing

The physiological manikin is a sweating manikin that runs manikin PC^2 human thermoregulation software[53]. It is architecturally very similar to the sweating manikin in that it is a 34 zone MTNW Newton manikin. There are some small architectural differences in the internal controllers as well as the surface areas of the individual sections but overall there are no significant differences in the build of the manikins. In addition, the physiological manikin connects to the power controls through the top of the head and also has a breathing capability. The physiological manikin uses Manikin PC^2 software which utilizes RadTherm® developed by ThermoAnalytics®. Manikin PC^2 is a Measurement Technology Northwest (MTNW) software interface. The underlying modeling is handled through RadTherm® running in the background. This software allows real time physiological data that would be comparable to the outputs of a human.

2.6.4.2 Virtual Modeling

RadTherm® can also be used as a purely virtual model. This is a human thermoregulation computer simulation model that solves a system of bio-heat transfer equations based on clothing and activity inputs that predict the human response. Much of the underlying model is based on the Fiala model and many of the physiological parameters come from the literature. There are other human thermoregulation models that exist such as the Stolwijk and the Wissler model. This particular model was chosen to be run in this study because North Carolina State University has worked in the past on helping to validate the model and it works with our sweating manikin system[54]. Figure 2.5 shows a visual of this modeling system. The model is based on a 50th percentile male in determining the local properties of the tissues[55]. The activity level of the manikin can be altered to produce different sweat rates based on the Fiala model of human thermoregulation. The Fiala model includes a passive system that models heat transport within the body and heat exchange in the body parts as well as an active system that simulates thermoregulatory body responses that occur[56]. The model is divided up into 20 body segments with between four and five tissue layers. These body layers include varying thicknesses of blood, bone, muscle, fat, and skin. Overall, the model solves the Bio Heat Transfer Equations which characterizes how heat moves from one compartment of the body to another compartment of the body[57]. In this case it shows how heat moves from the inside of the body where it is being produced to the surface of the skin and eventually the outside surface of the clothing where it can be released into the environment[57]. Specifically, body responses that it models include metabolic heating, shivering and sweating, respiration, and peripheral vasomotion[55].

RadTherm® expands on this model at very small segments (shown in Figure 2.5) to determine how heat transfer would occur very specifically throughout the body. The system is able to model the environmental heat exchange including evaporation of moisture and heat transfer from within the body to the skin surface and through the clothing and air layers[57]. Inputs into the RadTherm® model are environmental parameters, physical contact between the skin and the clothing, conduction, convection, radiation, the insulation values and the evaporative resistances of the clothing, and the work activity level. Specifically, the amount of contact the clothing has with the skin is important for the building of air layers between the clothing layers. Air layers are a significant source of insulation and therefore add to the barriers that the metabolic heat must pass through to escape from the body. The outputs include the clothing and skin temperatures, local and whole body heat fluxes, the core body temperature, and thermal sensation and comfort both locally and throughout the whole body[55]. It is used completely separate from the physiological manikin and can predict heat stress using steady-state insulative values and evaporative resistance measurements from either fabric level tests or from standard manikin tests[55][58].

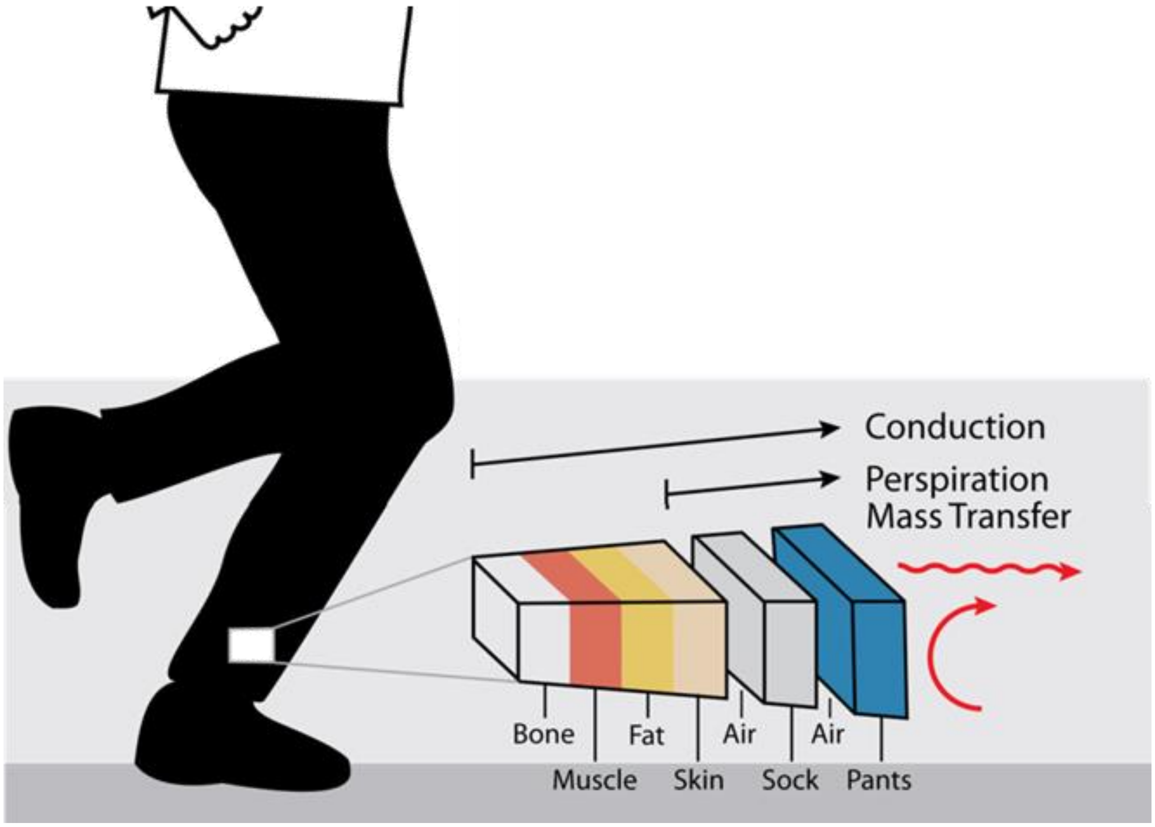

Figure 2.5: The Prediction of Mass Transfer used in the RadTherm® virtual model[55]

Validation of the model has significant practical implications because it will allow prediction of results for a wide variety of environments and work scenarios over a short period of time. It would facilitate planning for clothing wear trials, setting of operational guidelines, and selection of personal protective equipment based on wear conditions.

2.7 Overview

It has become clear that wildland firefighters are suffering from the effects of heat stress more often than they encounter problems from a lack of burn protection from their clothing[1]. Heat stress occurs when the body is unable to release the heat that builds up from metabolic processes into the surrounding environment through heat transfer. Clothing and the air layers between the clothing layers add an additional barrier for the heat to cross through. The environmental conditions play an important role in the release of this heat and must be taken into account when selecting clothing materials. Because there is a wide range of wildland firefighting environmental parameters, it is difficult to find a clothing material that is suitable for all environmental scenarios. The NFPA 1977 standard governing wildland firefighter protective clothing has attempted to combat heat stress related issues by developing The Total Heat Loss test as a means to measure how physiologically taxing garment materials are on the wildland firefighter. However, the present standard only looks at the outermost layer garment materials on a fabric level on the sweating hot plate. In addition, the minimum value set in the standard for garment materials to be used in the field does not have scientific research to support it. There are numerous other testing instruments that can be used to determine parameters associated with heat stress including the sweating manikin, the physiological sweating manikin, and physiological human wear trials in the lab setting. This research investigates Nomex® materials in both the fabric and garment level tests in wildland conditions to determine the effects that differing levels of protection have on the heat stress of wildland firefighters. In addition, the research will provide correlations between the different test instruments as well as compare a human wear trial with the same garments back to the test instruments showing which of those instruments give the most accurate prediction. Finally, a value for the THL requirement will be recommended if the sweating hot plate is determined to be an adequate method of measuring heat stress. An understanding of the minimum values necessary for the safe work of wildland firefighters will allow the balance between protection and relief of heat stress to be met.

3 Sweating Hot Plate Testing

3.1 Materials

Nine Nomex® fabrics were selected for initial bench level testing (Table 3.1) using a sweating hot plate and the ASTM F-1868 Standard Test Method for Thermal and Evaporative Resistance of Clothing Materials Using a Sweating Hot Plate. Nomex® is a meta-aramid often used in fire protection applications. A range in weights in both plain and twill weave, were tested to study the effect of fabric construction. Four different base layers were tested, selected to represent a range of undergarments worn by wildland firefighters. The nomenclature used for each of the fabrics was: the nominal weight X 100 followed by the type of weave indicated by a P for plain weave and a T for twill weave (ex. 330P is a 3.3 0z/yd^2 plain weave fabric). Base layers are indicated as follows: HC for heavy cotton, LC for light cotton, PE for polyester, and XG for the modacrylic/FR rayon blend.

Table 3.1: Garment Test Materials

ID	Material	Individual Characteristics	Weight (oz/yd^2)	Thickness (mm)	Weave/ Knit
330P	100% Nomex® IIIA: blend of Nomex® meta-aramid (93%), Kevlar® para-aramid (5%), and antistatic fiber (2%)[59]		3.4	.18	Plain
450P			4.7	.40	Plain
600P			6.5	.46	Plain
750P			8.1	.54	Plain
950P		Shelltite® water-repellant finish	10.3	.64	Plain
550T			5.7	.48	Twill
600T			6.2	.47	Twill
680T			7.3	.47	Twill
770T			8.0	.62	Twill
HC	100% Cotton		7.1	.58	Knit
LC	100% Cotton		4.7	.46	Knit
PE	100% Polyester	High wicking capabilities	4.6	.40	Jersey
XG	Modacrylic/ FR Rayon Blend	Flame retardant and wickable	5.2	.49	Knit

Some departments have specific restrictions on the base layers that are worn in the field. Other departments make recommendations on what should be worn and in some cases the firefighters do not follow these recommendations. The recommendations are usually a cotton t-shirt or any t-shirt that is not a thermoplastic material, meaning that it melts. The Cal Fire, a wildland firefighting department in southern California, standard issue heavy cotton t-shirt is a required part of the uniform in the Cal Fire department. The lightweight cotton t-shirt is lighter and thinner and therefore allows more heat transfer. A 100% polyester t-shirt was used because it is a highly wickable fabric. However, it is recommended that firefighters do not use this fabric because it is a thermoplastic and melts at high temperatures. One reason to investigate this base layer is to see whether it shows any promise of actually performing better since firefighters are putting themselves at a safety risk by wearing it. If in fact the 100% polyester base layer is performing better, it is a benchmark to work toward in the future with safe material alternatives. If not, it is helpful to be able to have scientific proof to give to firefighters. Finally, the XG base layer is a modacrylic/FR rayon blend being used in a currently ongoing Natick study researching wildland firefighter clothing. This base layer is wickable, like the 100% polyester t-shirt, also flame retardant. Three replicates of each of the fabrics were tested on the sweating hot plate as a single layer. In addition, combinations of the Nomex® shells and the base layers were tested. Finally, the 600P/750P and 330P/330P were tested as double layer systems with and without the heavy cotton base layers.

The materials that were tested in combination with a base layer first looked into the Standard Issue Cotton Base Layer at every weight of plain weave Nomex fabric. In addition, the mid weight plain weave Nomex and the 7.7 oz/yd^2 twill weave Nomex fabrics were tested with each of the individual base layers. There were three double layer configurations tested on the sweating hot plate. Two layers of the lightest weight plain weave Nomex, two layers of the mid-weight twill weave Nomex, and a relatively heavy double layer combination that was expected to give a relatively low total heat loss value were all tested. Finally the double layer light weight plain weave and the double layer heavy combination were also tested with the Standard Issue cotton base layer.

3.2 Guarded Sweating Hot Plate Procedure

All of the materials were tested on a Measurement Technology Northwest (MTNW) Sweating Guarded Hotplate: Model 10.5 housed in a Lunaire Model CEO 932-4 Steady

State/Stability Test Chamber[60], [61]. The temperature conditions were controlled by a Partlow 1160+ Temperature controller and the humidity conditions were controlled by a Partlow 1160+ Humidity controller[61]. The tests were run at 25°C and 65% RH and a 1 m/s wind speed. ThermDAC v3.2.6 software, developed by MTNW, was used to measure the parameters necessary to calculate the thermal and evaporative resistance. The important Sweating Guarded Hotplate specifications are as follows:

- 10” square test plate
- 5” guard ring
- 20.2” ± 0.5” x 20.2” ± 0.5” sample size
- Porous surface plate
- Gravity- fed reservoir and fluid supply system
- Copper test plate, rings, and lower guards
- Two ambient temperature sensors, one relative humidity sensor, and one air velocity sensor

Figure 3.1: Hot Plate in Environmental Chamber

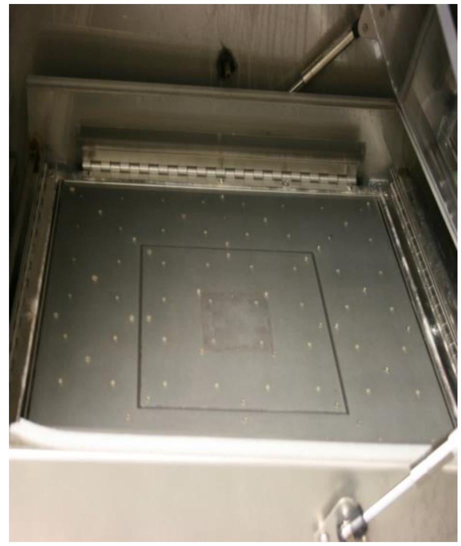

Figure 3.2: Close-Up of the Porous Sweating Hot Plate

3.3 Hot Plate Results

The total heat loss (Q_t or THL), the dry component, mostly convective and therefore referred to as the convective component, of the total heat loss (C), the evaporative component of the total heat loss (E), the average intrinsic thermal resistance (R_{cf}), and the average apparent intrinsic evaporative resistance (AR_{ef}) of the composites were measured and reported. Q, C, and E are reported in watts per meter squared (W/m^2), the R_c is reported in Kelvin times meter squared per watt ($K \cdot m^2/W$), and the R_e is reported in ($kPa \cdot m^2/W$).

In addition, single layer and composite weights and thicknesses were measured for the fabrics. The thicknesses were measured on the Kawabata Evaluation System (KES) Compression tester.

Detailed sweating hot plate data is summarized in Appendix B. The three replicates of each material were averaged to produce the total heat loss shown in Figures 3.3 and 3.4. Figure 3.3 shows the total heat loss of the outer shells without the base layers, where the convective component is in red and the evaporative component in blue. The black line across the graph at 450 W/m^2 indicates where the minimum THL requirement is set for NFPA 1977. The green line represents 6 METS or 348 W/m^2, which indicates the approximate work rate of a wildland firefighter. The MET, or Metabolic Equivalent of Task, is a physiological measure that characterizes the energy cost of a physical activity. 348 W/m^2 is the equivalent energy expenditure, through heat, the firefighter would produce. These lines show that the NFPA standard THL requirement is higher than the average work rate of the wildland firefighter; so if these measurements are correct, theoretically all metabolic heat should be released during work and there should be no heat buildup. Figure 3.4 shows the same outer shells measured on the hot plate along with the base layers. The total heat loss is separated into the convective and evaporative components on this graph as well. Both the NFPA standard and the work rate of the wildland firefighter are included on this graph. Table 3.2 shows the statistical differences between the fabrics tested on the sweating hot plate.

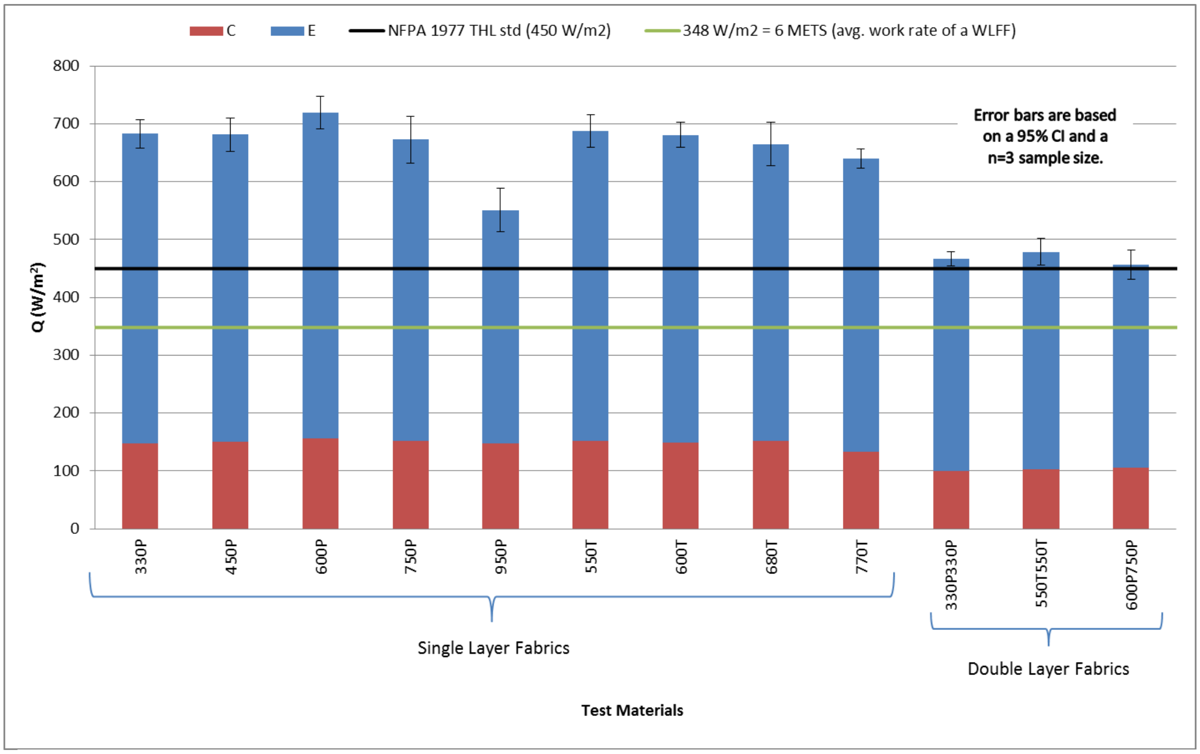

Figure 3.3: Total Heat Loss of Single and Double Layer Fabric Systems (without base layers)

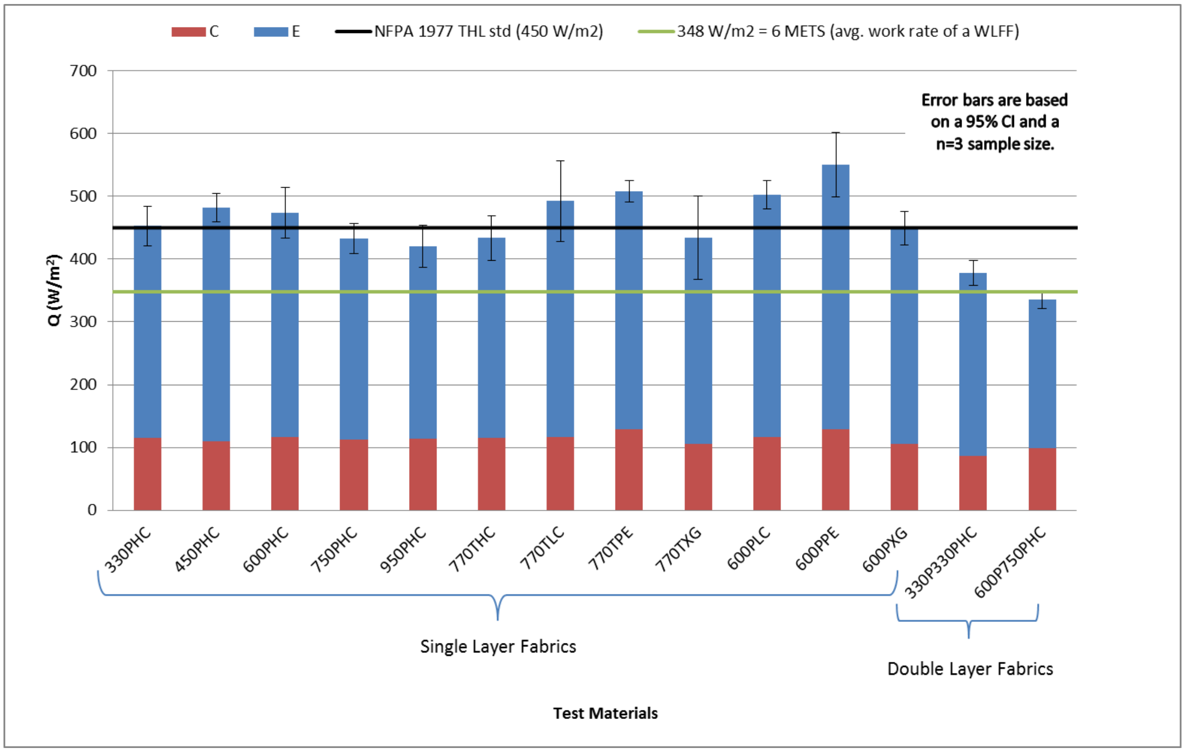

Figure 3.4: Total Heat Loss of Single and Double Layer Fabric Systems (with base layers)

Table 3.2: Differences of Garments in Total Heat Loss on the Sweating Hot Plate

Garments	330P	450P	600P	750P	950P	550T	600T	680T	770T	HC	LC	PE	XG	330PHC	450PHC	600PHC	750PHC	950PHC
330P		NS	*	NS	**	NS	NS	NS	**	NS	NS	***	**	***	***	***	**	***
450P			***	NS	***	NS	NS	NS	*	NS	***	***	NS	***	***	***	***	***
600P				*	***	*	*	**	**	**	**	***	*	***	***	***	***	***
750P					**	*	NS	NS	*	NS	*	***	**	***	***	***	***	***
950P						**	**	***	**	***	***	***	**	**	**	*	***	**
550T							NS	NS	**	NS	NS	***	**	***	***	***	***	***
600T								NS	**	NS	*	***	*	***	***	***	***	***
680T									NS	NS	*	***	*	***	***	***	***	***
770T										**	**	***	NS	***	***	***	***	***
HC											NS	***	NS	***	***	***	***	***
LC												***	*	***	***	***	***	***
PE													***	***	***	***	***	***
XG														***	***	***	***	***
330PHC															**	NS	NS	*
450PHC																NS	**	**
600PHC																	NS	**
750PHC																		NS
950PHC																		
770THC																		
770TLC																		
770TPE																		
770TXG																		
600PLC																		
600PPE																		
600PXG																		
330P330P																		
550T550T																		
600P750P																		
330P330PHC																		

NS non-significant, * significant at the 90% level, ** significant at the 95% level, *** significant at the 99% level

Table 3.2 Continued

770THC	770TLC	770TPE	770TXG	600PLC	600PPE	600PXG	330P330P	550T550T	600P750P	330P330PHC	600P750PHC
***	***	***	***	***	***	***	***	***	***	***	***
***	**	***	***	***	**	***	***	***	***	***	***
***	***	***	***	***	**	***	***	***	***	***	***
***	**	***	***	***	***	***	***	***	***	***	***
**	*	*	***	**	NS	***	***	**	***	***	***
***	**	***	***	***	**	***	***	***	***	***	***
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***	***	***	***	***	***	***	***	***	***	***	***
***	**	***	**	***	**	***	***	***	***	***	***
NS	*	***	NS	*	***	NS	NS	*	NS	***	***
**	NS	**	NS	NS	***	**	NS	NS	NS	***	***
**	NS	**	NS	NS	***	**	NS	NS	NS	***	***
NS	*	**	NS	***	**	**	***	**	*	***	***
**	*	***	NS	***	**	NS	**	***	*	*	**
	*	***	NS	**	**	NS	*	***	NS	**	**
		NS	NS	NS	***	*	NS	NS	NS	**	***
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3.4 Hot Plate Discussion

The evaporative component for all of the fabrics is overwhelmingly larger than the convective component. In Figure 3.3, all of the single layer plain weave fabrics had a similar total heat loss value except for the heaviest weight (9.5 oz/yd^2 fabric) which had a significantly lower THL than the other test fabrics. There is no significant difference observed between a twill and plain weave fabric of similar weights on the hot plate. The double layered fabrics, indicated as 330P330P, 550T550T, and 600P750P all showed similar values but were significantly lower than the single layer fabrics. Without the base layer, all of the fabrics passed the requirement of NFPA 1977 and could therefore be made into a garment for wildland firefighters. Even the double layer heavy fabric passed the requirement. The error bars in both Figure 3.3 and 3.4 represent a sample 95% confidence interval with a n=3 sample size.

Figure 3.4 shows the effects of a base layer on heat loss through fabric systems. Many of the configurations gave a THL lower than the NFPA 1977 minimum requirement. The 3.3 oz/yd^2, 4.5 oz/yd^2, 6.0 oz/yd^2 plain weave fabrics all measured with the heavy cotton base layer (330PHC, 450PHC, and 600PHC) still would pass the 450 W/m^2 NFPA 1977 requirement if garments were required to be tested with their base layer, but the 7.5 oz/yd^2 and 9.5 oz/yd^2 plain weave fabrics with the heavy cotton base layers (750PHC and 950PHC) would not. The 7.7 oz/yd^2 twill fabrics that were tested with all of the different base layers would pass with the lightweight cotton t-shirt material (4.7 oz/yd^2) and the polyester base layer (4.6 oz/yd^2) . The heavy weight cotton (7.1 oz/yd^2) base layer and the modacrylic/FR rayon blend base layer (5.2 oz/yd^2) would not pass. For the midweight (6.0 oz/yd^2) plain weave fabric that was tested with each of the base layers, all fabrics would the requirement except for the one with the modacrylic/FR rayon blend which would fail. Both the double layer light weight plain weave with the heavy cotton base layer (330P330PHC) and the double layer heavy combination with the heavy weight cotton (600P750PHC) would fail the NFPA 1977 standard THL requirement. All of the fabric configurations gave THL values higher than the average work rate of the wildland firefighter (348 W/m^2) except for the double layer heavy combination with the heavy cotton base layer. Therefore, the results of the sweating hot plate indicates that there should be no buildup of metabolic heat inside of the suits during the wildland firefighter's work period outside of a heavy double layer combination.

3.4.1 Correlation between Fabric Construction and THL

Figure 3.5 shows the correlation between total heat loss (THL) and the measured thickness of the fabrics and layered systems. Outliers for the correlations in this section are defined as data points that are more than 10% away from the predicted THL based on the fabric's weight or thickness. One of the outliers of the correlation was the polyester, which had a higher THL than expected for its thickness. This may be because of its wicking capabilities since the evaporative component plays a large part in the THL. This is important to note because many wildland firefighters put themselves at risk by wearing polyester shirts as a base layer. This result indicates that the polyester may actually be beneficial so safer alternatives may need to be investigated. The double layer 3.3 oz/yd^2 plain weave and the double layer 3.3 oz/yd^2 plain weave with the heavy cotton base layer which both had lower THLs than the correlation predicts based on their thicknesses. This may be because of the air layers that are introduced when using a multi-layer fabric. Overall, as the thickness of the fabric or composite increased, the total heat loss decreased. The single layer fabrics are indicated as red data points and the double layer fabric systems are indicated as blue data points. As expected, the single layer fabrics were generally thinner and the composites, excluding the double layer light weight plain weave, were generally thicker.

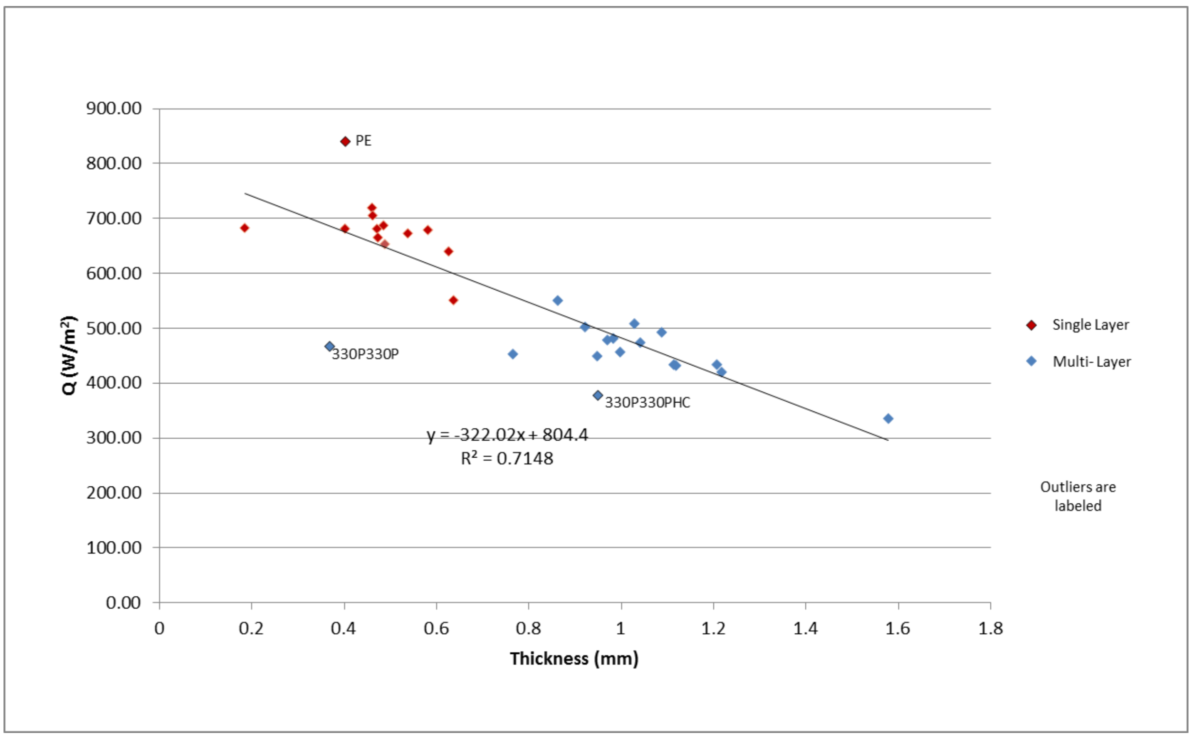


Figure 3.5: Correlation between THL and Thickness for All Fabric Configurations

Figure 3.6, shows the correlation between the total heat loss and the weight of the fabrics and composites. As the weight of the fabrics increased, the total heat loss (THL) of the fabric system decreases. This is an expected result, because fabric thermal insulation is known to correlate with weight and thickness[62]. The total heat loss versus the weight showed a stronger correlation but also had far more outliers. In addition to the outliers in the correlation between total heat loss and thickness, the 6.0 oz/yd^2 plain weave with the modacrylic/FR rayon blend base layer, the 7.7 oz/yd^2 twill fabric with the modacrylic/FR rayon blend base layer, and the single layer 3.3 oz/yd^2 plain weave fabric with the heavy cotton base layer were lower than the correlation. The 9.5 oz/yd^2 plain weave and the double layer heavy combination with the heavy cotton base layer had higher THLs than the correlation predicted. In both correlations, polyester could have a higher total heat loss than the other fabrics because of its wicking properties. The water on the surface of the sweating hot plate is able to move the heat from the plate surface to the air much faster than the other fabrics causing more heat loss overall. The 950HC fabric performs better than its weight indicates that it should because the finish likely adds additional weight to the fabric that does not add additional insulation. However, it is unclear why the heavy double layer fabric (600P750PHC) performs better because the air layers should cause it to perform at a lower level than its weight would indicate. In addition, the light weight Nomex® has a low total heat loss in almost all of its configurations but it is unclear why because it is a Nomex® IIIA fabric like all of the other fabrics. The fabric was slightly shinier and softer than the other fabrics however, which may indicate that there was some type of finish on that fabric.

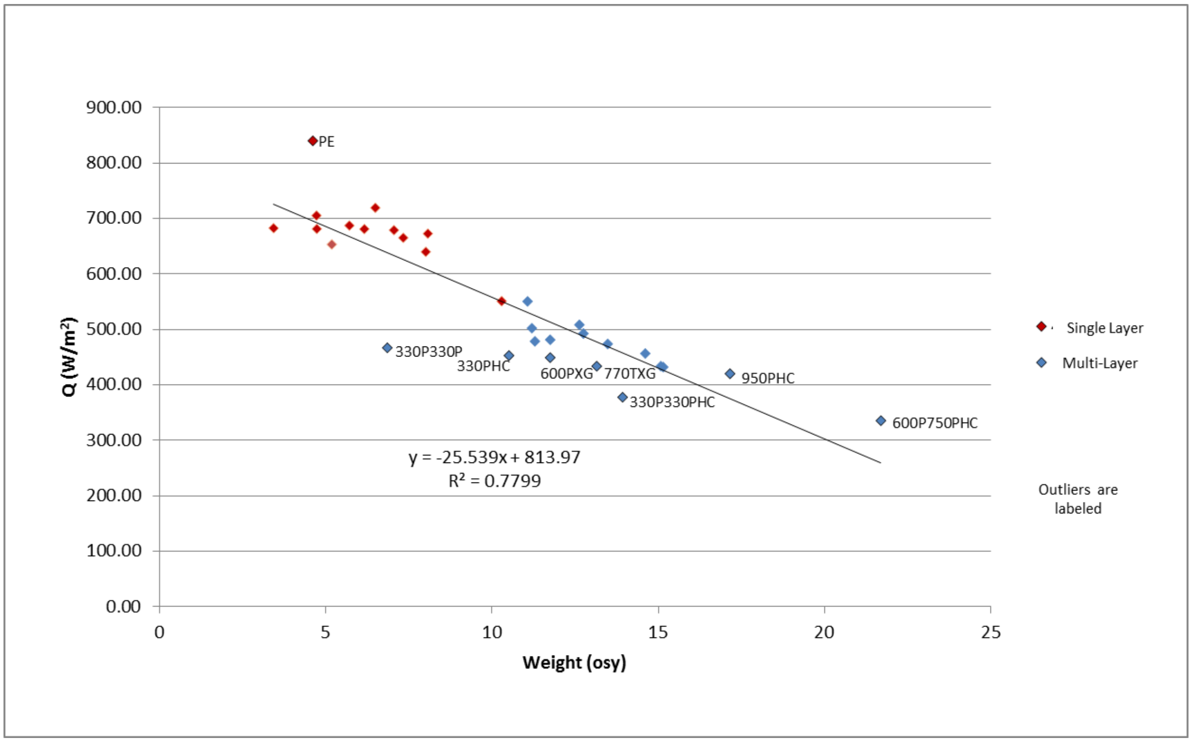


Figure 3.6: Relationship between Fabric Weight and THL for All Fabric Configurations

4 Sweating Manikin Testing

4.1 Materials

Eight fabric configurations were made into non-commercial garments and tested on the sweating manikin (Table 4.1). These fabrics were chosen for garment level tests due to their range of THL values and other fabric/garment construction characteristics that were being investigated such as the weave, the base layer, and the presence of reinforcements as defined by NFPA 1977.

Table 4.1: Test Garments and Clothing Configurations

Base Garment Fabric	**Corresponding Figure**	**Plate THL (W/m^2)**	**Distinguishing Characteristics**
330P	Figure 4.1	683	Standard reinforcements (~318 in^2)
750P	Figure 4.2	673	Standard reinforcements (~318 in^2)
750P extra reinforcements	Figure 4.3		~1020 in^2 SA of reinf.
750P no reinforcements	Figure 4.4		0 in^2 SA of reinforcements
770T	Figure 4.5	640	Standard reinforcements (~318 in^2)
770T	Figure 4.6		Tested with the XG base layer
950P	Figure 4.7	551	has a Shelltite™ water repellant finish
600P750P	Figure 4.8	457	Standard reinforcements (~318 in^2); double layer garment
Cal Fire	Figure 4.9		4.5 oz/yd^2 jacket and outer pant; 7.5 oz/yd^2 station pant
USFS	Figure 4.10		6.0 oz/yd^2 plain weave jacket, 7.7 oz/yd^2 twill pant
Standard Structural Turnout	Figure 4.11	230	Contains a thermal barrier, moisture barrier, and an outer shell
Shorts and T-shirt	Figure 4.12		

Fabrics 330P, 750P, 950P, and 770T were made into single layer wildland uniforms with the standard amount of reinforcements. The standard garment has approximately 318 in^2 of surface area on the garment. Reinforcements are characterized by the NFPA as any extra layers that are sewn onto the wildland firefighting garment. This may include trim, pockets, knee pads, and elbow pads but does not include seams used in making the garment. The

600P750P configuration was made into a double layer wildland garment with the standard amount of reinforcements as well. This allowed investigation of the highest THL configuration and also the effects of using a double layer system. In addition, fabric 750P was made into a wildland uniform with extra reinforcements (1020 in^2 of surface area) and also into a separate garment with no reinforcements (0 in^2 of surface area). Since NFPA 1977 has a maximum amount of reinforcements that could be on a garment, this was an important variable to investigate. Reinforcements add extra layers of material and further hinder the release of heat from within a garment. None of the garments exceeded the maximum surface area of reinforcements allowed in NFPA 1977.

In addition, four other readymade garments were tested on the manikin. One of the standard USFS wildland garments and a standard Cal Fire wildland garment were tested on the manikin. These are two garments that are currently used in wildland firefighting. Also, a turnout suit was tested to represent a lower limit of THL for what may be used in wildland firefighting. The turnout construction was composed of a 7.5 oz/yd^2 Nomex® IIIA plain weave outer layer, 2.7 oz/yd^2 polytetrafluoroethylene (PTFE) laminated to Nomex® E-89 moisture barrier, and 8 oz/yd^2 100% aramid batt and 100% garnetted aramid thermal barrier[63]. A turnout garment is the heaviest garment that would conceivably be worn while wildland firefighting which sometimes occurs in cases where structural firefighters are called to do wildland firefighting duties. All of the garments were tested with a 7.1 oz/yd^2 cotton t-shirt (fabric HC). In addition, the 7.7 oz/yd^2 garment was tested with the 5.2 oz/yd^2 modacrylic/FR rayon blend base layer (fabric XG). Finally, an ensemble consisting of just shorts and the 7.1 oz/yd^2 cotton t-shirt was tested. This provides an upper bound of manikin

THL. No wildland firefighters should be responding in shorts and a t-shirt but it provides a limit for what is conceivably possible in this extreme case. In total, twelve different garment configurations were evaluated. All garments were additionally tested with a standard wildland firefighting helmet, gloves, underwear, socks, a belt, and athletic shoes. The helmet used had a thermoplastic shell with an extra-large full brim, a Flex-Gear® ratchet sizing 6-point suspension, a cotton brow pad, and reflective lime-yellow strips. A hole was drilled into the top of the helmet so that it would slide over the top of the manikin and sit on its head properly. The gloves worn by the manikin were 100% leather work gloves. The underwear was a size medium 100% cotton boxer brief to fit the manikin. The socks were 89% cotton, 9% polyester, 1% nylon, 1% spandex crew-style socks. The shoes were US size 11 generic sneaker-type shoes with Velcro straps chosen to fit the manikin. Finally, the belt used was a size 36 fully adjustable cotton belt with leather trim. Figures 4.1-4.12 show pictures of the suits on the sweating manikin.

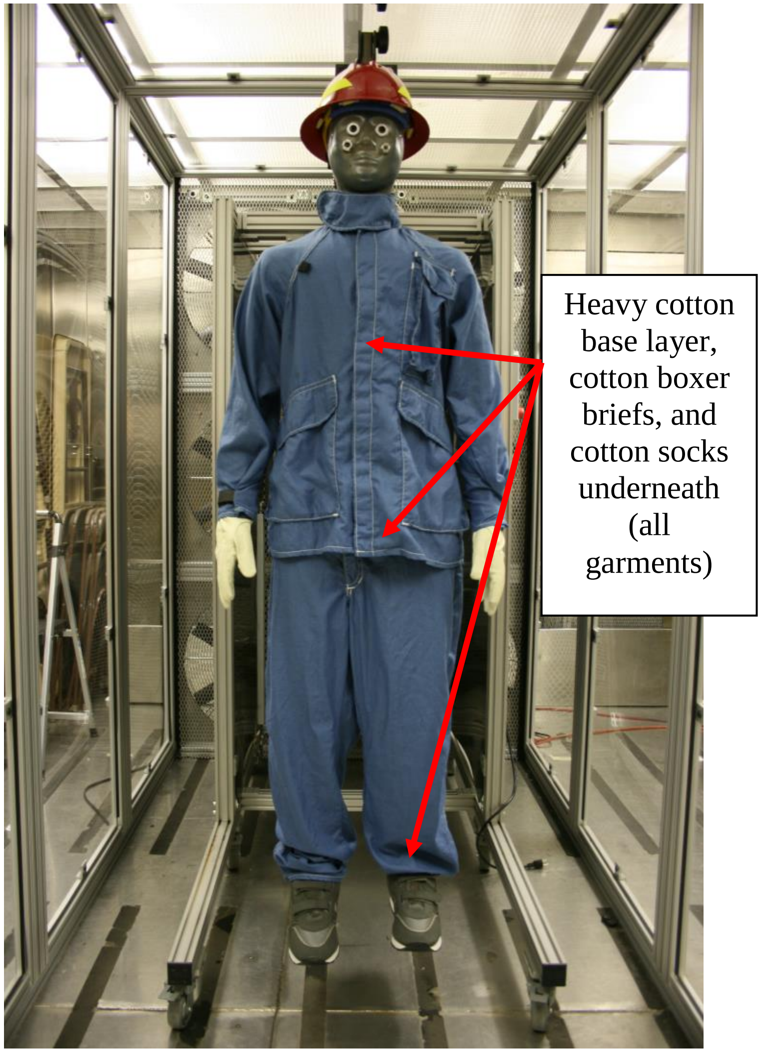


Figure 4.1:330PHC

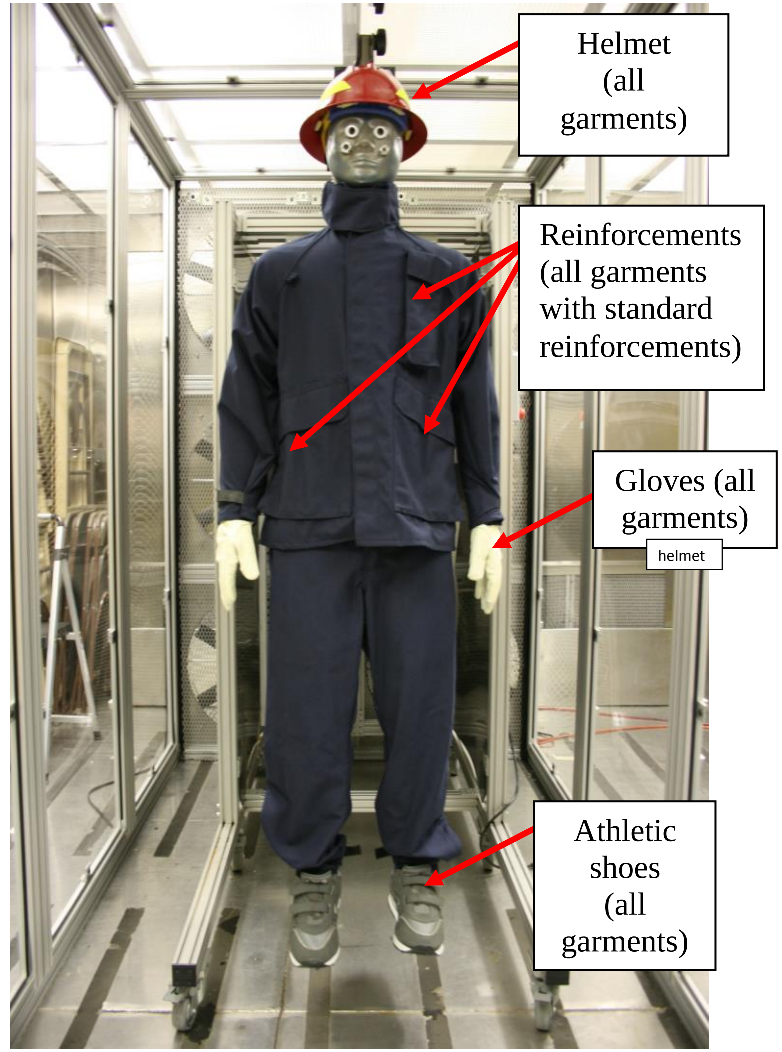


Figure 4.2: 750PHC

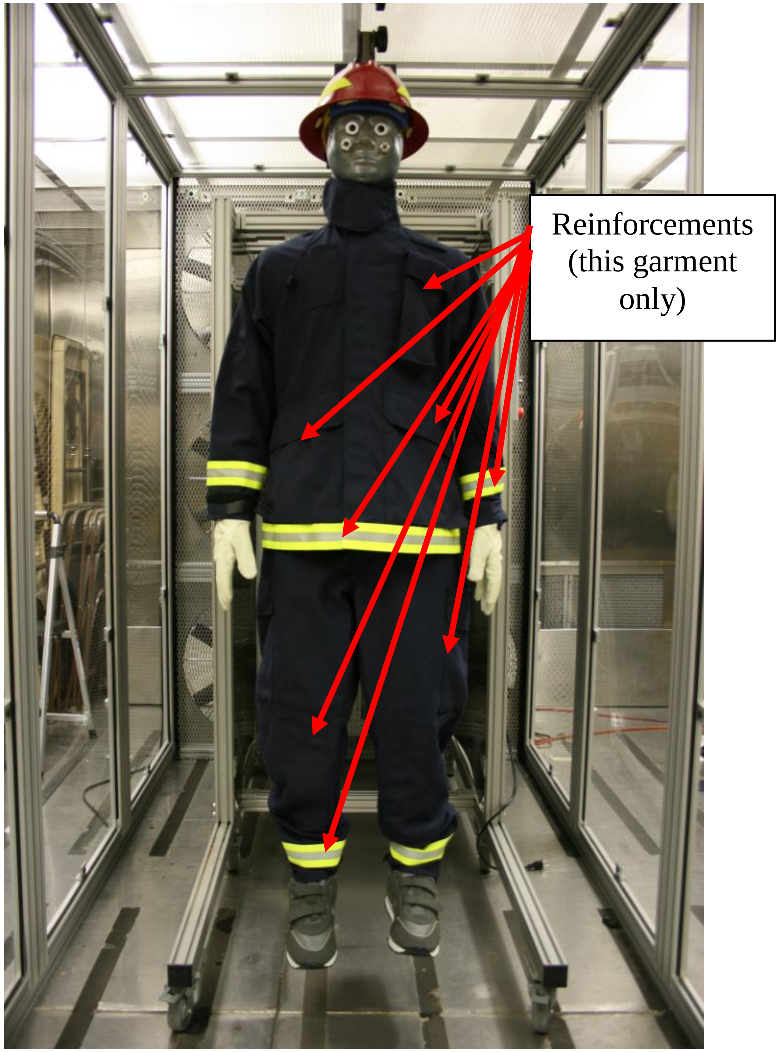


Figure 4.3: 750PHC extra reinforcements

Figure 4.4: 750PHC no reinforcements

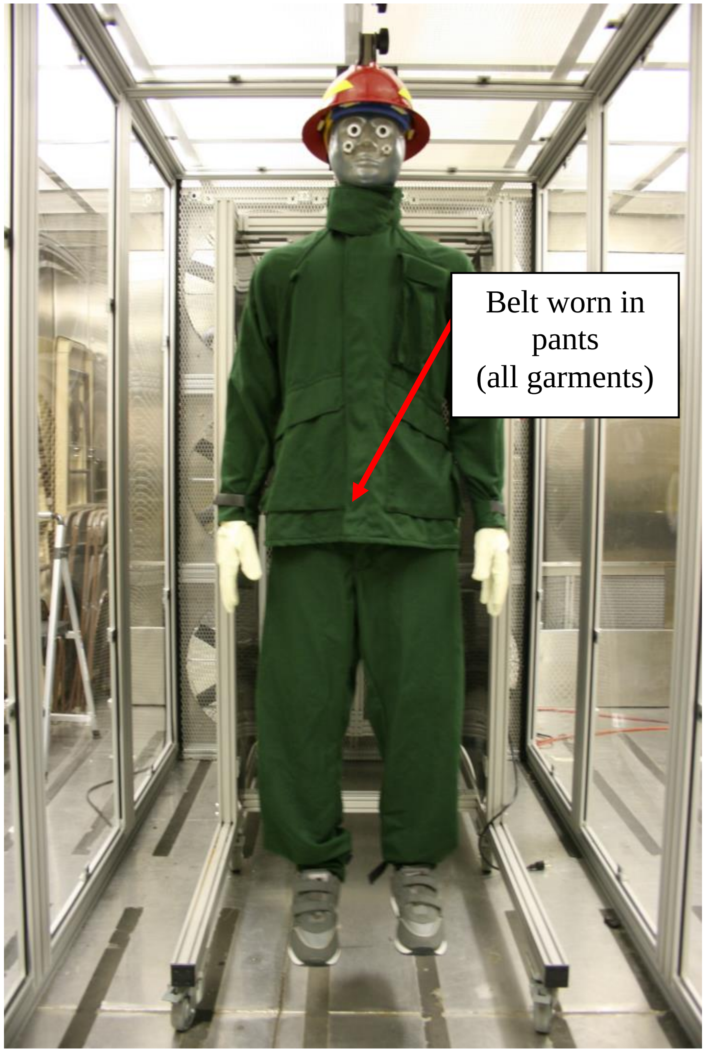


Figure 4.5: 770THC

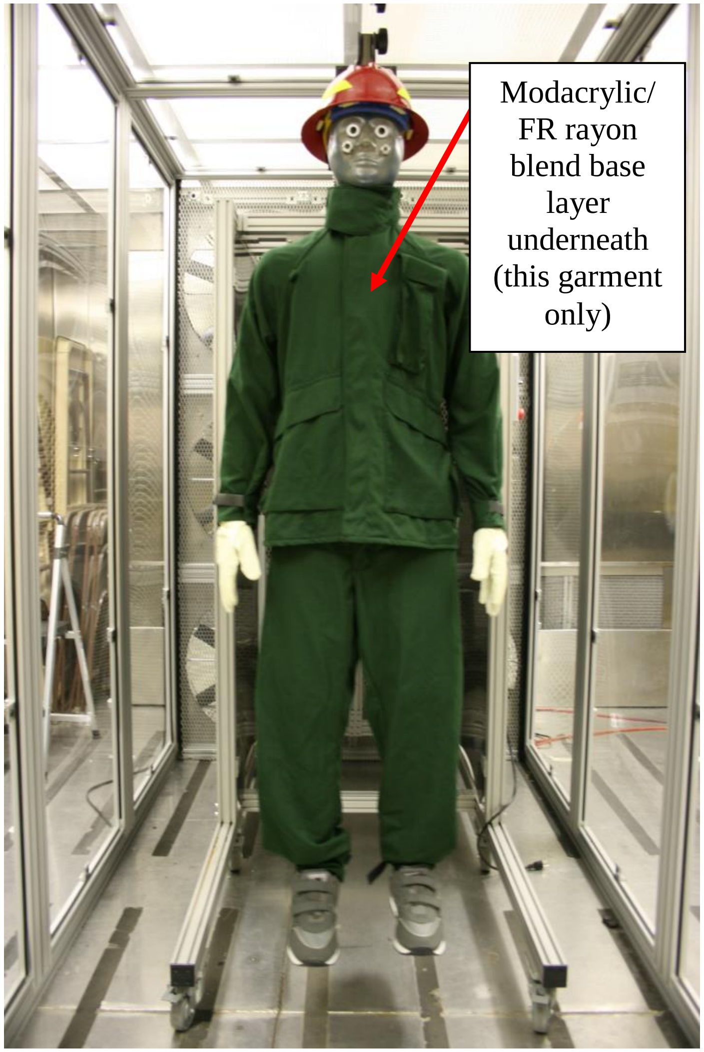


Figure 4.6:770TXG

Figure 4.7: 950PHC

Figure 4.8: 600P750PHC

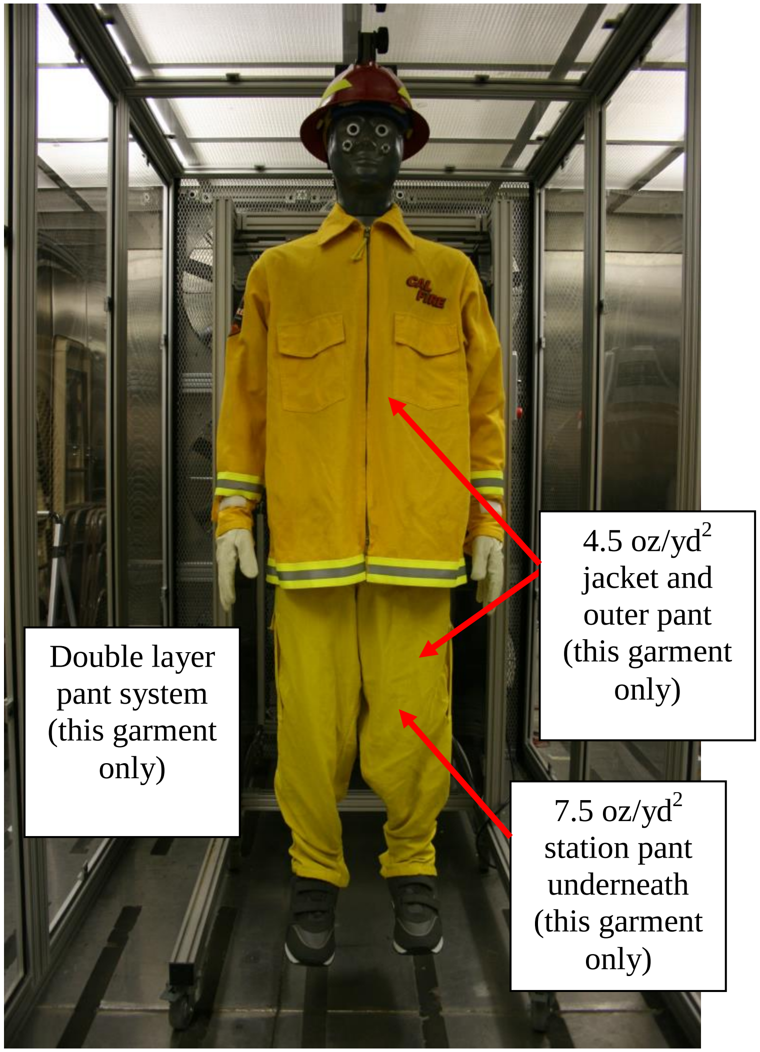


Figure 4.9:CalFire Standard Issue

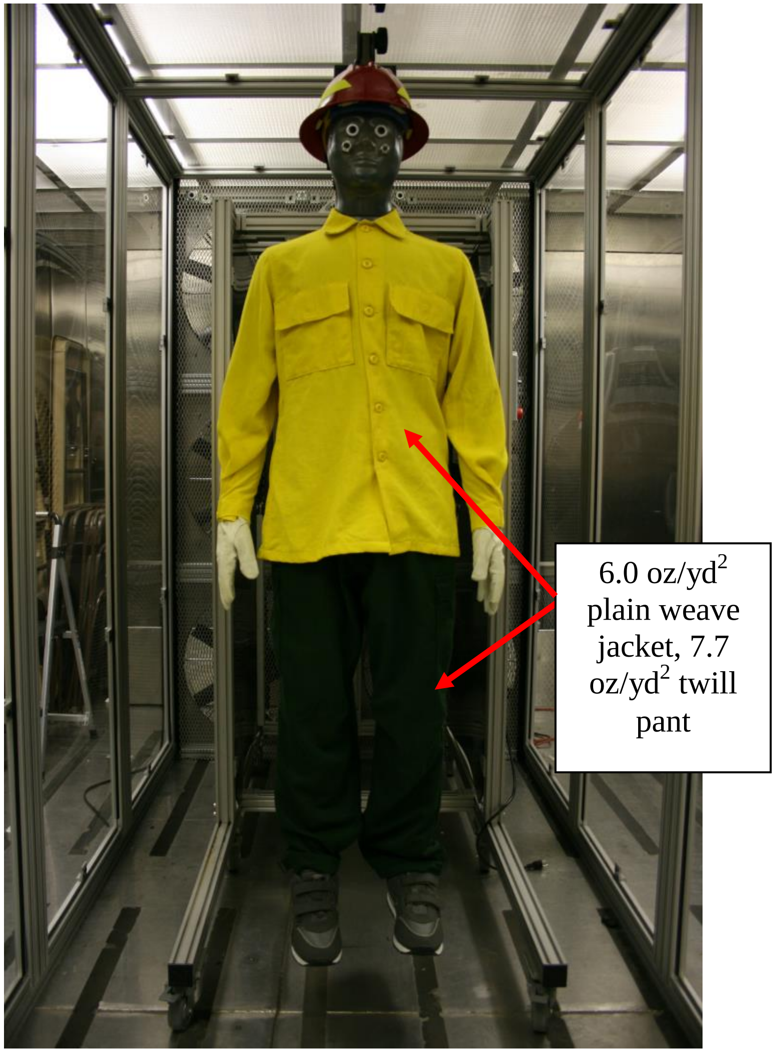


Figure 4.10: USFS Standard Issue

Figure 4.11: Structural Turnout Suit

Figure 4.12: Shorts and Standard Issue Cotton T-shirt

4.2 Sweating Manikin Test Procedure

The thermal resistance testing on the Sweating Manikin was conducted under the ASTM F 1291: Standard Test Method for Measuring the Thermal Insulation of Clothing Using a Heated Manikin[46]. The only variation from the standard was a 1 m/s wind speed used to match the wind speed of the sweating hot plate. Conditions were maintained in the environmental chamber within the range given by the standard at 20°C and 40% relative humidity. A bare manikin test was conducted, followed by each of the garments tested in three replicates.

For evaporative resistance testing, ASTM F 2370: Standard Method for Measuring the Evaporative Resistance of Clothing Using a Sweating Manikin was followed[47]. Once again, a 1 m/s wind speed was used which varied from the standard. In addition, the environmental chamber was kept at approximately 35°C and a 40% relative humidity. A wet bare manikin test was conducted, followed by each of the garments tested in three replicates.

4.3 Sweating Manikin Results

The results for the sweating manikin testing are shown in Table 4.2. The average predicted total heat loss (manikin THL) for each of the suits is given as well as the dry and wet components of the average total heat loss (C, E). In addition, the average thermal resistance (R_{cl}) and the average evaporative resistance (R_{ecl}) are also shown.

Table 4.2: Sweating Manikin Testing Results

Sample	Manikin THL (W/m^2)	C (W/m^2)	E (W/m^2)	R_{cl} ($K \cdot m^2/W$)	R_{ecl} ($kPa \cdot m^2/W$)
330PHC	216	60	156	0.128	0.016
750PHC	205	57	148	0.136	0.018
750PHC no reinf	205	57	148	0.136	0.018
750PHC extra reinf	193	54	138	0.145	0.019
950PHC	184	57	127	0.137	0.022
770THC	212	58	154	0.135	0.017
770TXG	213	58	155	0.135	0.017
650P700PHC	175	49	126	0.165	0.022
USFS	204	56	148	0.138	0.018
Cal Fire	173	49	124	0.165	0.022
Structural	109	37	72	0.230	0.043
Shorts and T-shirt	372	103	269	0.059	0.007

Figure 4.14 shows the sweating manikin total heat loss results. The predicted total heat loss is on the Y axis in W/m^2 and each of the garments is on the X axis. Like the sweating hot plate graph, the black line indicates the NFPA 1977 THL minimum requirement for the hot plate and the green line indicates the average work rate of a wildland firefighter. The total heat loss is divided into the convective component shown in red and the evaporative component shown in blue.

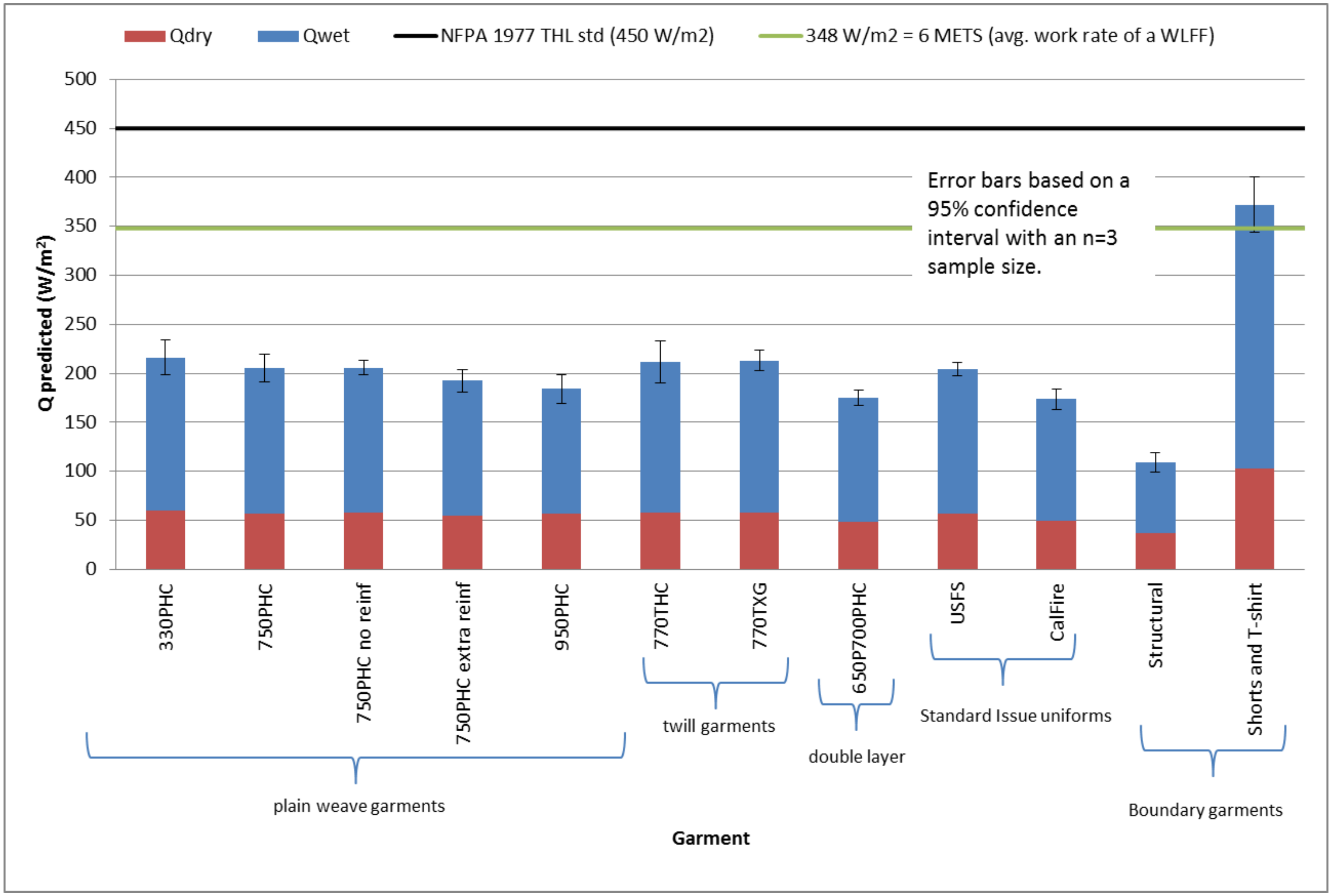


Figure 4.13: THL of Wildland Garments measured on the Sweating Manikin (compared to a Structural Firefighter Suit and Short and a T-shirt)

Table 4.3: Differences of Garments in Total Heat Loss on the Sweating Manikin

Garments	330PHC	750PHC	750PHC no reinf	750PHC extra reinf	950PHC	770THC	770TXG	650P700PHC	USFS	CalFire	Structural	Shorts and T-shirt
330PHC	-	**	NS	**	**	NS	NS	***	NS	***	***	***
750PHC		-	NS	**	**	NS	NS	**	NS	***	***	***
750PHC no reinf			-	***	*	NS	NS	**	NS	***	***	***
750PHC extra reinf				-	NS	NS	*	*	NS	***	***	***
950PHC					-	***	**	**	**	NS	***	***
770THC						-	NS	***	NS	**	***	***
770TXG							-	***	***	**	***	***
650P700PHC								-	***	NS	***	***
USFS									-	**	***	***
CalFire										-	***	***
Structural											-	***
Shorts and T-shirt												-
NS non-significant, * significant at the 90% level, ** significant at the 95% level, *** significant at the 99% level												

4.4 Discussion of Sweating Manikin Data

Figure 4.14 shows the differences in total heat loss between the different garments. Table 4.3 shows the significance between these differences. The structural garment is an example of an extremely heavy garment that could be worn for wildland firefighting, though it could not be certified, and the garment that consists of just shorts and a t-shirt represents the least amount of clothing that would conceivably be worn. This gives a guideline of the best and the worst possible THL values that would be seen in wildland firefighting scenarios, though shorts and a t-shirt would likely never be worn. It is difficult to see any differences between the wildland firefighting garments when the two extreme garments are included. It is important to note that if the garments tested on the manikin were held to the same NFPA 1977 standard as the sweating hot plate, none of the garments would pass. The manikin THL values are much lower than the hot plate THL values because air layers increase insulation and reduce the total heat loss from the body. In addition, only the shorts and t-shirt would be able to dissipate the heat that is being produced by a wildland firefighter during a routine days work (348 W/m^2) if the predicted heat loss values is indicative of the actual heat loss to the environment. It is important to acknowledge that this predicted heat loss value is for a very specific, mild environment (25C, 65RH, 1m/s air flow) and that the actual amount of heat loss would be subject to the fire ground conditions.

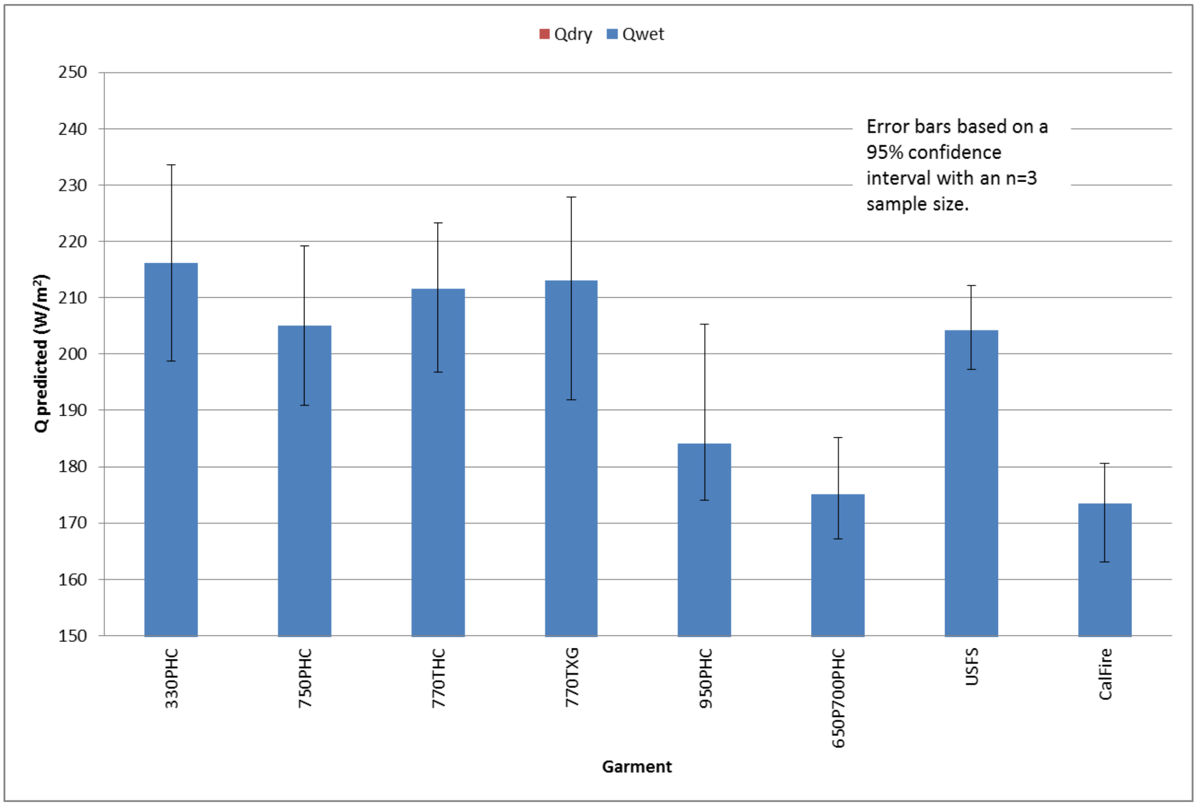


Figure 4.14: Sweating Manikin THL

Figure 4.15 shows a comparison between clothing systems that use the twill fabrics (770THC) compared to the clothing systems of a similar weight that uses the plain weave fabric (750PHC). The twill weave gives a slightly higher total heat loss value than the plain weave even though it is slightly heavier. This is likely because twill weave fabrics have more floating yarns than plain weave fabrics and therefore allow for more air permeability. Higher air permeability allows for a higher amount of heat released from the garment. When comparing two garments with the 7.7 oz/yd^2 twill weave and the two different base layers

(770THC and 770TXG) there is no remarkable difference. Figure 4.16 shows a comparison of manikin THL between only the garments that were tested in the wear trial.

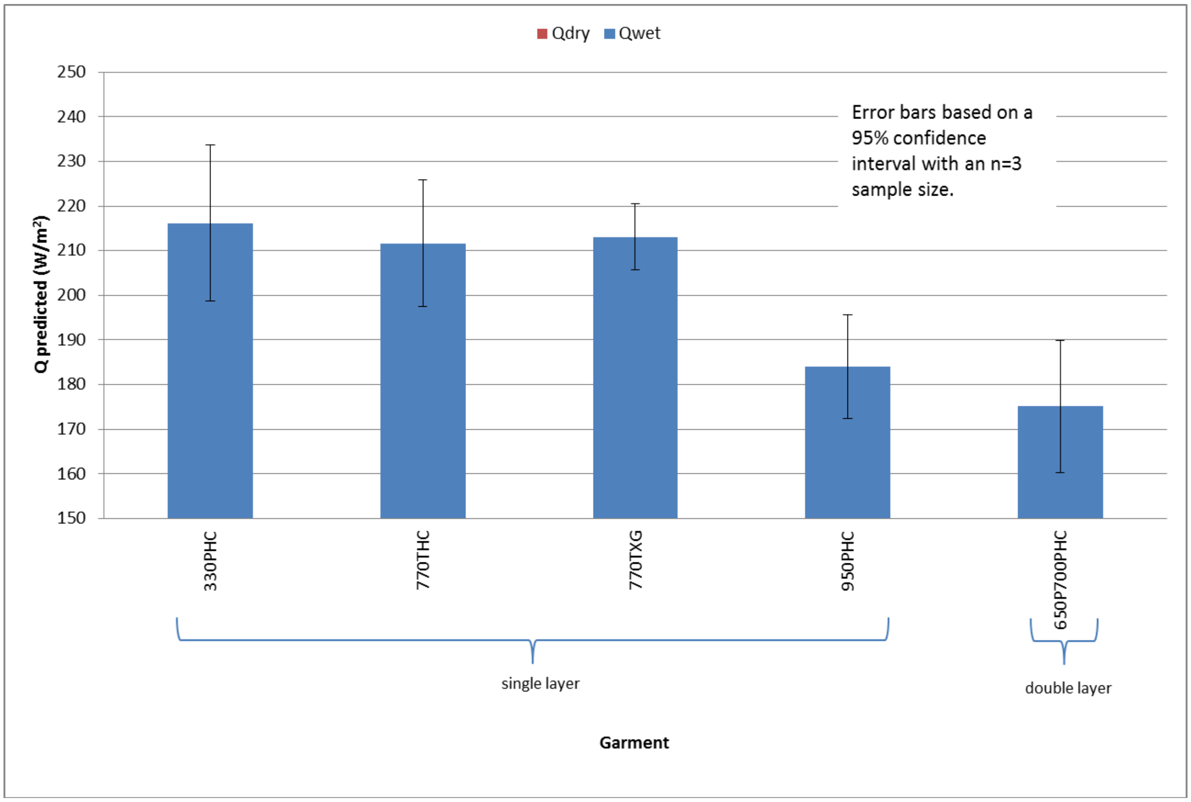


Figure 4.15: THL from the Sweating Manikin for Garments used in the Wear Trial

The results show that there is a small difference between the 3.3 oz/yd^2 plain weave and the 7.7 oz/yd^2 twill with both base layers when compared to the heaviest plain weave (9.5 oz/yd^2) and the double layer garments. The double layer garment has a lower average

THL than the 9.5 oz/yd^2 plain weave. Finally, Figure 4.17 shows no difference between the standard garment(with reinforcements) and one with no reinforcements. However, when there are extra reinforcements there is a drop in the total heat loss. With 318 in^2 of reinforcements on the standard garment and 1020 in^2 of reinforcements on the garment with extra reinforcements, there is a much larger jump in surface area of the reinforcements between the standard garment and the one with extra reinforcements than between the one with no reinforcements and the standard garment. Also the reinforcements on the garment with extra reinforcements are greater evaporation barriers than pocket material, so this could also add to the effect. The manikin diagrams showing the heat loss by section for each garment can be found in Appendix C.

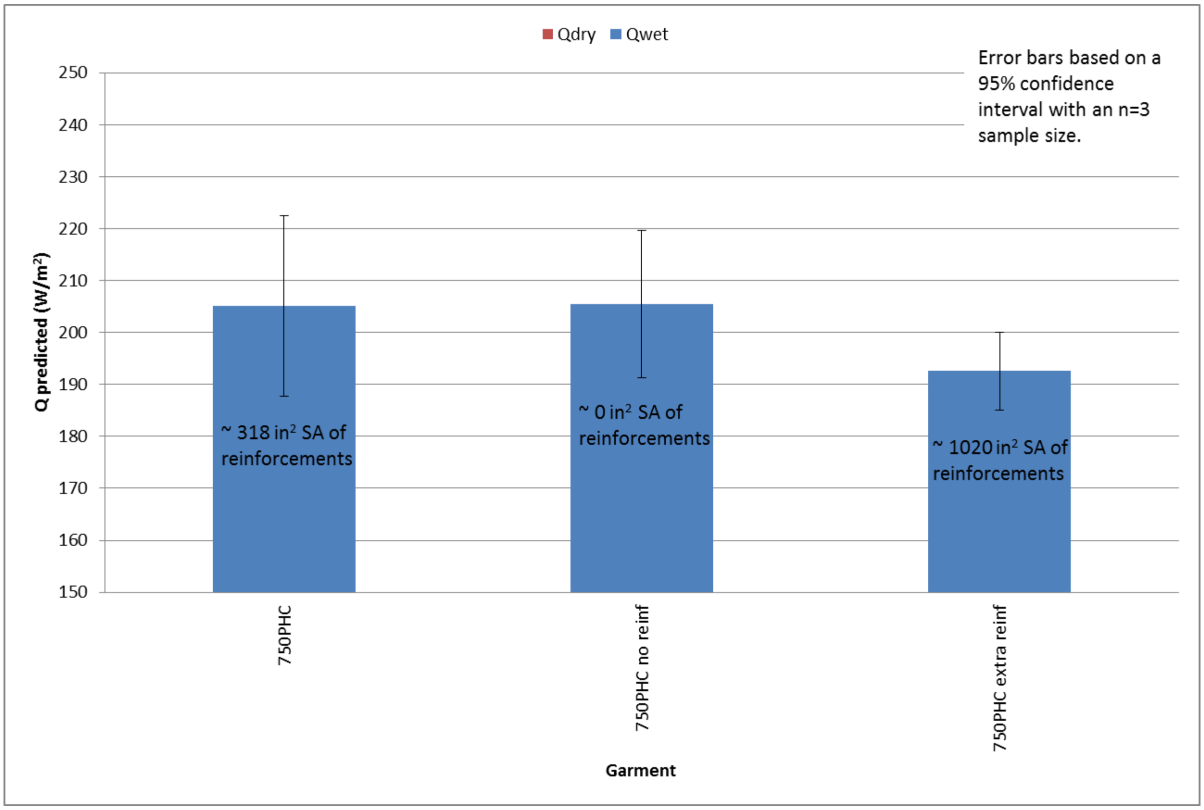


Figure 4.16: Effect of Added Reinforcements on Garment THL

4.4.1 Correlations between Plate and Manikin THL

When the correlation between the total heat loss on the sweating hot plate and the total heat loss on the manikin was examined in wildland garments of the same design there was a good correlation (Figure 4.18). However, when the correlation includes garments that do not have the standard amount of reinforcements, the correlation relationship is no longer as strong. Figure 4.19 shows that since there are differing amounts of reinforcements on the garments, the measured THL value would differ. However, because they do not exceed the maximum surface area of reinforcements before the total heat loss of the reinforcements must be measured with the outer shell according to NFPA 1977, only the outer shell would be measured. Therefore, they would have the same total heat loss value on the sweating hot plate. This finding demonstrates one of the primary differences between the manikin and the hot plate. The manikin can account for differences in garment design whereas the hot plate cannot. The good correlation between the hot plate THL and “manikin THL” values can be mainly attributed to two factors: 1) the base composite tested on the manikin covered the majority of the manikin (all except head, hands, and feet), and 2) the manikin garments were all of the same design and fit worn with the same set of accessories.

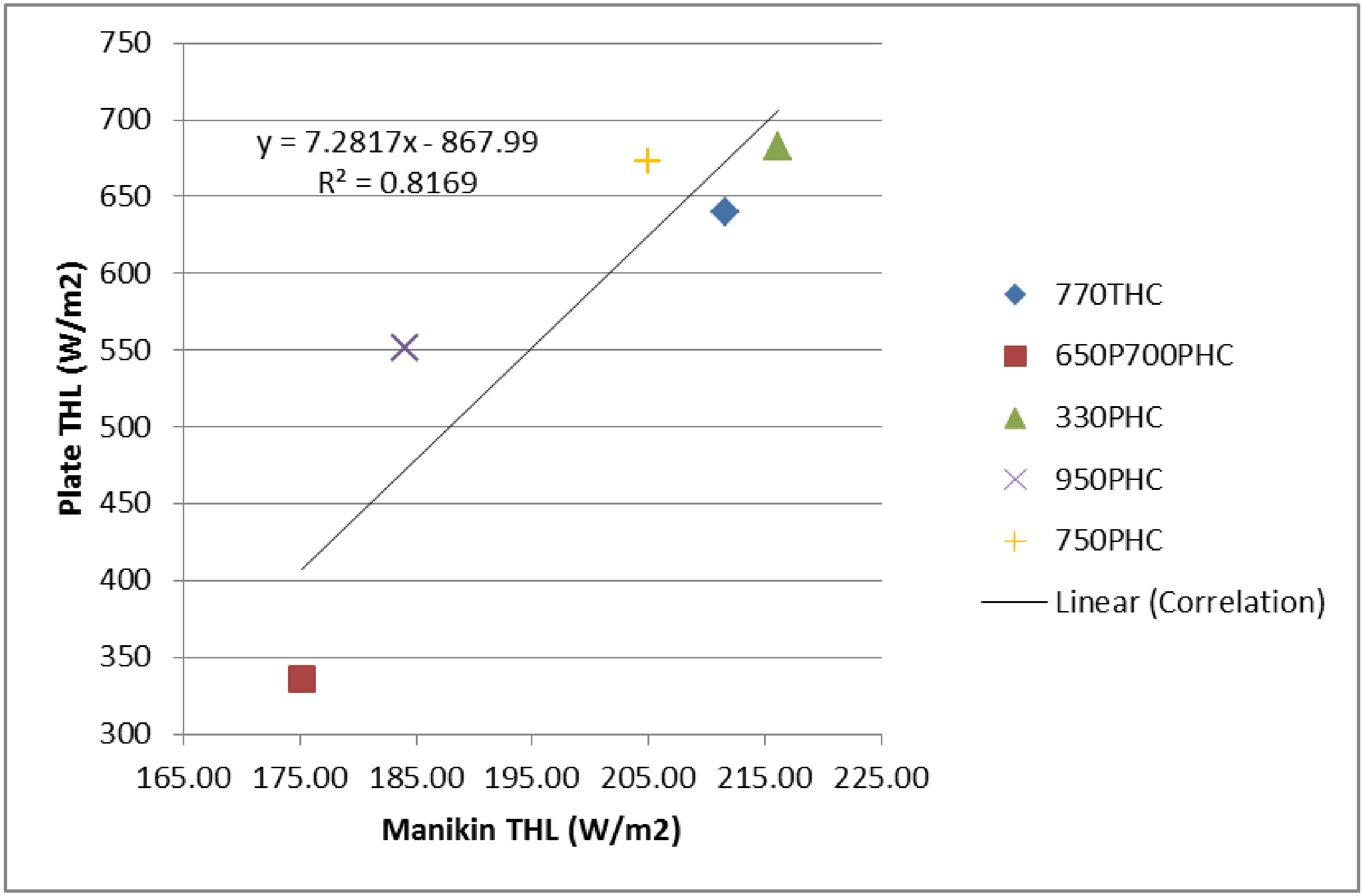


Figure 4.17: Plate THL vs. Manikin THL (wildland garments with the same design)

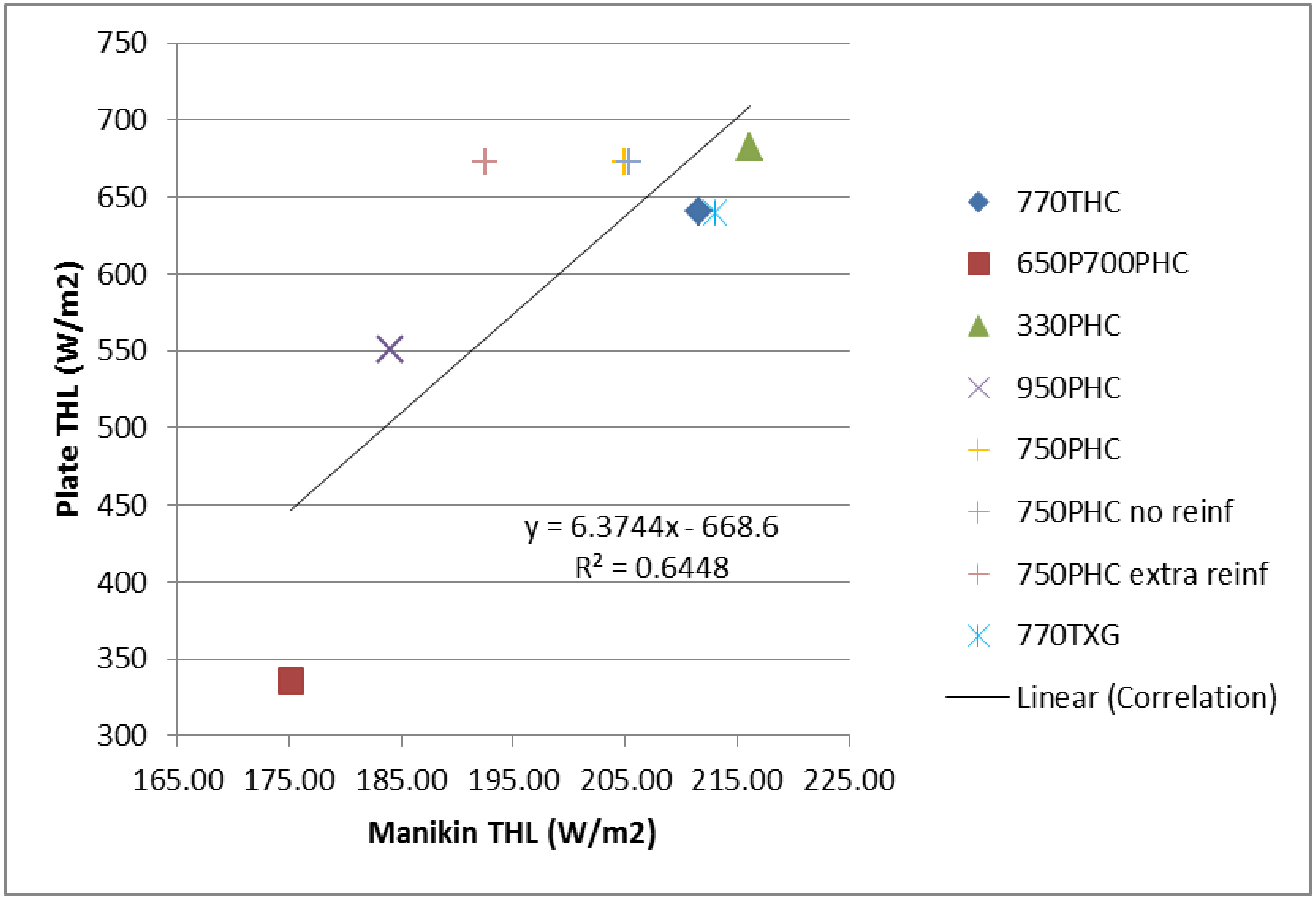


Figure 4.18: Plate THL vs. Manikin THL (all Wildland Garments)

5 Physiological Wear Trial

5.1 Materials

From the fabric tested on the sweating hot plate, one garment type was made from each of the 330P, 950P, and 600P750P double layer configurations to be tested with the 7.1 oz/yd^2 cotton base layer (HC). These were selected because they represented a range of THL values and weights. In addition, two garments were made from the 770T material, one to be tested with the heavy cotton base layer (HC) and one to be tested with the modacrylic/FR rayon blend base layer (XG). This allowed for a physiological and a subjective comparison between two of the base layers. Fewer garments were tested in the physiological wear trial because of time constraints and the cost of testing a large number of garments on all of the subjects. As with the sweating manikin tests, all of the subjects tested each of the garments with the same gloves, socks, underwear, and belt. Each of the subjects wore their own athletic shoes, instead of wearing leather boots that would normally be worn to avoid blisters that may be experienced with such a lengthy, repetitive walking motion. All garments were fit to each individual and were a size large, a size medium, or a combination of the two for the jacket and pants. Subjects were selected to ensure that they fit the garments.

Table 5.1: Test Garments (Physiological Wear Trial)

Garment	Base Layer	THL value (W/m^2)
3.3 oz/yd^2 Nomex® plain weave	7.1 oz/yd^2 cotton	683
7.7 oz/yd^2 Nomex® twill weave	7.1 oz/yd^2 cotton	640
“	5.2 oz/yd^2 modacrylic/ FR rayon blend	
9.5 oz/yd^2 Nomex® plain weave with a Shelltite™ water repellant finish	7.1 oz/yd^2 cotton	551
6.0 oz/yd^2 Nomex® plain weave and 7.5 oz/yd^2 Nomex® plain weave double layer system	7.1 oz/yd^2 cotton	457

5.2 Wear Trial Protocol

5.2.1 Developing the Protocol

There were several criteria that were important for the final chosen parameters to meet: the protocol should represent a realistic use scenario for wildland firefighters. It was important that wildland firefighting conditions be simulated in the environmental chamber and that active firefighter subjects were used. It was also important that the protocol highlighted any existing differences between test garments. Therefore, the protocol could not be so mild that the firefighters could complete the tasks with ease no matter what garment they were wearing, nor could it be so stressful that the task was impossible to complete with even the lightest and most breathable test suit. Finally, it was important that the protocol be compared to the instrument level tests and other heat stress studies that had been conducted on wildland firefighter clothing. This would allow correlations to be established and clothing effects to be examined.

An initial protocol was developed with the information based on wildland firefighting conditions and past studies (Table 5.2). Particularly, the studies done at the University of Montana and at the Auburn University were used as a guideline since wildland firefighting wear trials were conducted in environmental chambers for similar investigations.

Table 5.2: Initial Wear Trial Test Protocol (based on previous studies)

Overall Time	120 minutes
Active Time	105 minutes (5 minute rest period at 30, 60, and 90 minutes)
Activity Type	treadmill walking at 3.5 mph (grade altered to reach work rate)
Rest Type	stop movement and put down pack
Activity Level (Work rate)	6 METS (using VO2 method)
Hydration	new 300 mL bottle of water provided at each rest (subjects can drink as much as necessary during the test but must continue movement during non-rest periods)
Gear	required pack (possibly 45 lb. used in work capacity test)
Wind	5mph toward face of subject (approximately 2.235 m/s)
Temperature	35°C
RH	40%
Radiant Source	side radiant load with three 250 W infrared lamps

After the initial protocol was developed, it was altered to facilitate the study of the instruments. Specifically, the wind speed was changed to 1 m/s to match the hot plate and instrumented sweating manikin test conditions. Because of the number of garments being tested in the protocol, the number of subjects involved in the test, and the time available to complete testing, the part of the wear trial spent in the environmental chamber could not exceed two hours. Finally, the activity level remained at 6 METS. Modeling was then used to determine the temperature and humidity to be used in the protocol and whether the radiant load would have a positive or negative effect on the wear trial. The approach to determining these settings was first to use a simple model using predicted work tolerance time based on sweating manikin clothing parameters to determine the temperature and humidity. A predetermined max heat accumulation before heat stress was used in the model with the following equation:

Heat Stored = Metabolic rate – (Conduction + Convection + Radiation + Evaporation)[24]

Using the sweating manikin thermal and evaporative resistance values, the heat loss to various environments and related tolerance times were predicted using a maximum amount of heat stored of approximately 80 kcal[64]. However, this model did not account for respiration, peripheral vasomotion, shivering, and external work. Figure 5.1 shows the output from these model calculations based on heat loss measured using the sweating manikin procedure. Each of the green dotted lines represent the predicted work tolerance time for each temperature, 22°C, 26°C, 30°C, 34°C, and 38°C, over a range of relative humidity for the USFS uniform. The Cal Fire is plotted in the same way and is indicated with orange solid lines. Each of the lines are labeled by temperature and garment. This model shows that with the lower temperatures and relative humidity, the conditions are too mild and an infinite amount of time is required for significant heat buildup. However, with the higher temperatures and relative humidity, the conditions would be too stressful and there would be little difference between the suits. The target range based on this simple model was between approximately 30°C and 34°C and a relative humidity of between approximately 25% and 35%.

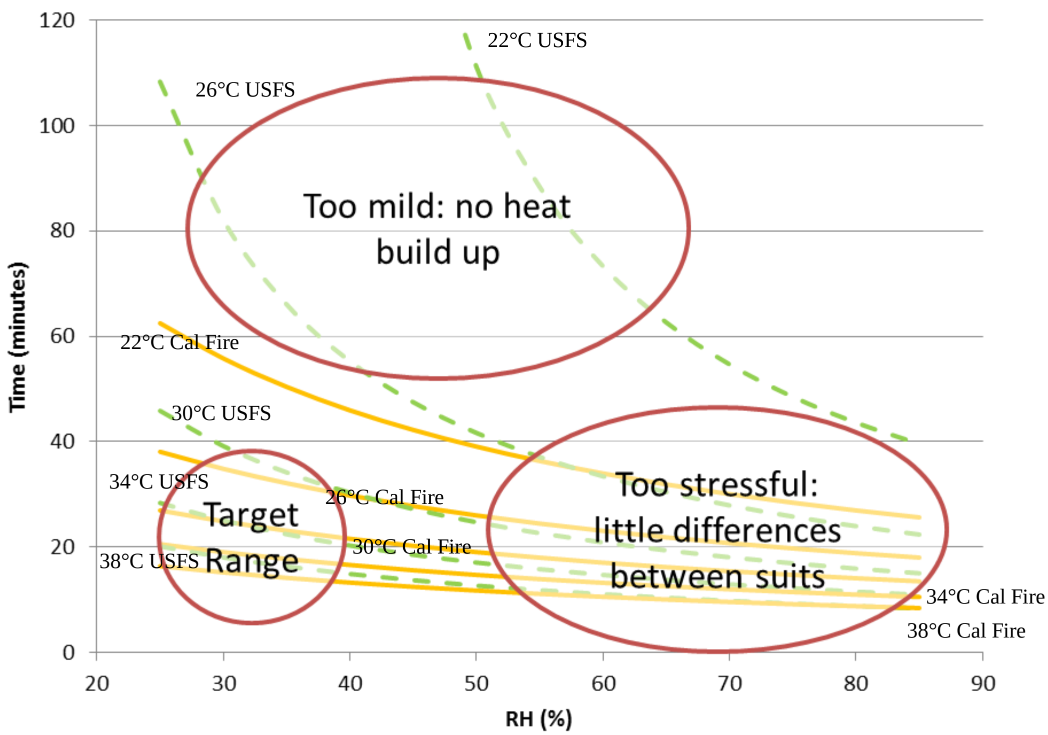


Figure 5.1: Work Tolerance Times based on Sweating Manikin measurements of Test Garment Heat Loss

This was a somewhat crude calculation to get a starting point as to where to focus more sophisticated (but more time-consuming) modeling efforts. At this stage of planning, we did not have access to the virtual model component separate from the physiological manikin so modeling required exposing the manikin to the target test scenarios.

The second part of the modeling approach involved using the physiological manikin to measure the predicted human response in a real-time setting at the target conditions specified by the work tolerance time prediction. This allowed for the refinement of the final conditions. The physiological manikin uses thermoregulation modeling incorporated into an instrumented sweating manikin to predict clothing and skin temperatures, as well as core body temperature. The human response that may be seen in an actual physiological wear trial could be predicted using this system. In order to validate that the physiological manikin was a good modeling technique, the protocol of the University of Montana physiological wear trial was replicated and though the model over-predicted somewhat, similar results were achieved[50]. The University of Montana study investigated the physiological response of their subjects in USFS and Cal Fire uniforms and found a large difference between them. The goal was achieve the differences seen in the University of Montana study among the garments in this study. Once the model was validated, the conditions within the target range indicated by the work tolerance times were tested. In addition, the effect of using a radiant load was investigated. Of the conditions tested, 34°C, 30%RH and approximately 750 W/m^2 showed maximal differences. Figure 5.2 below shows the final output from the conditions compared to the University of Montana study replication. It shows that a similar 1°C peak difference in the core body temperature can be achieved with a shorter protocol of two hours rather than three, when using the conditions found from conducting this model.

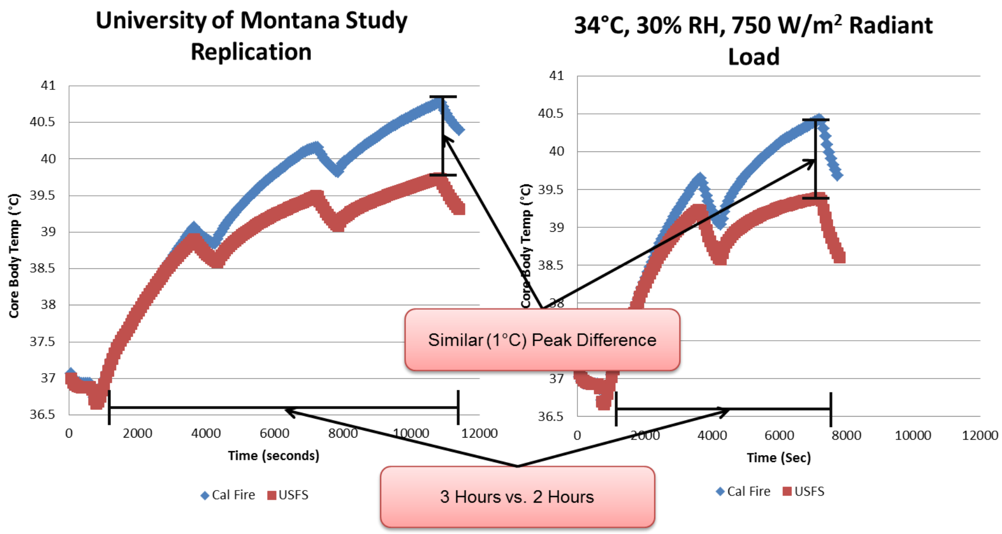


Figure 5.2: Manikin Model Results for Physiological Wear Trial Conditions

5.2.2 Preliminary Tests

Finally there was an initial set of tests done with a few of the wildland firefighters to ensure that differences could be seen with the garments under that setup. This testing showed that the MET rate was too high (subject were being pulled from testing because they had reached their maximum heart rate), the back pack was too heavy making the protocol extremely difficult, and the radiant load was too high and could not be distributed evenly at such high levels. Because of this, it was decided that the backpack would no longer be used in the wear trial, the firefighters would work at a 5 MET work rate, and the radiant load would be reduced to 250W/m^2.

The testing conducted in the physiological wear trial was approved by the Institutional Review Board at North Carolina State University and the Federal Emergency Management Agency (FEMA) in the Department of Homeland Security (DHS).

5.2.3 Preliminary Subject Fitness Testing

Before the beginning of the wear trial, each of the subjects were required to come in to the lab to complete a VO_2 test and to determine the treadmill grade necessary to reach the required MET rate for each subject. These tests were conducted on the CardioCoach™ VO_2 Fitness Assessment System from KORR Medical Technologies Inc. and the CardioCoach™ Monitor 3 PC Software. Necessary information such as the subject's age and weight were entered into the system before conducting the test. When finding the necessary grade, the subjects wore an oxygen mask designed to connect to the system and a heart rate strap that also connected with the system. The oxygen mask was connected to the system through a plastic hose that would measure the content of the subjects' expelled air. The test started at 3mph and a 0% grade. The MET rate was recorded over time on the software. When the MET rate leveled out the grade was increased until the necessary MET rate was reached. For the VO_2 testing, the speed was gradually increased then the incline was increased until the test indicated that the subject was at their anaerobic threshold. Then, the workload was increased until the subject could no longer continue. Finally, this test was followed by a recovery phase. The subjects wore shorts, a t-shirt, and athletic shoes to complete these tests. The grades recovered from these tests were used to ensure that the subjects were working at the correct MET rate during the wear trial.

For the actual wear trial, predicted grades from ACSM equations were used because the backpacks were no longer being worn in the study and the original fitness testing was done with the backpacks. The metabolic cart was used to verify that the treadmill settings (from ACSM prediction equations) yielded the desired work rate.

5.2.4 Physiological Wear Trial

Each subject took a Respironics® core temperature capsule at least three hours prior to testing in the wear trial. This would ensure that the capsule was deep in their abdomen by the time the test began. All trials were carried out in the morning beginning at approximately 9am. Before the arrival of the subjects each morning, four Respironics® dermal patches designed to read the core temperature were activated. Upon arrival, each of the subjects were connected to VitalSense® Telemetric Monitoring system software to ensure that their core temperature capsule was working. Following confirmation of an existing core temperature reading, they were examined by a nurse or EMT to ensure that they were healthy enough to participate in the wear trial.

The weights of the individual pieces of each ensemble and the ensemble as a whole were weighed before the subject put them on. Nude weights of the subjects were taken wearing the provided underwear, the dermal patches in the locations shown in Figure 5.3, and a heart rate monitor strap and device.

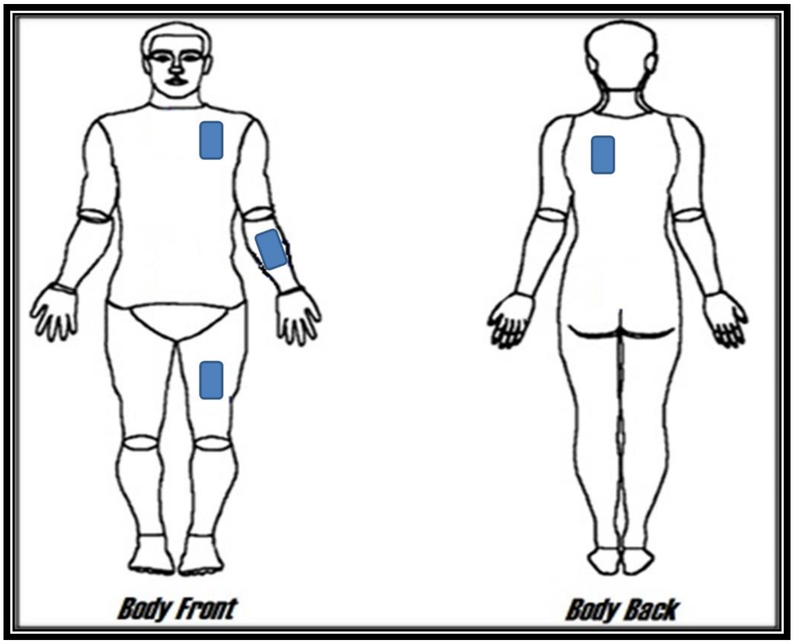


Figure 5.3: Locations of the Dermal Patches for the Reading of Skin Temperature

After the nude weight was taken, the subjects put on the rest of their ensembles and were weighed again fully dressed. The test then began and Table 5.3 shows the protocol that was followed. Figure 5.4 shows the setup of the chamber. The temperature was set at 34°C, 30% relative humidity, and a wind speed of 1 m/s. Four radiant lights positioned behind the subjects imposed approximately 250 W/m^2 of radiant heat on each of the subjects. In the chamber, the subjects completed two work and rest cycles. Each cycle consisted of 50 minutes of walking on a treadmill at 3mph and the grade necessary to achieve a 5 MET work rate followed by 10 minutes of rest. During the ten minute rest periods, at minute 0, 60, 120, and 130, the subjects took a subjective survey about the clothing and a reaction time test.

Screen shots of the reaction time test can be found in Appendix D. After the test was complete, the subjects were weighed with their full ensemble and once again wearing just the underwear, dermal patches, and heart rate monitor strap and device. The subjects were examined by a nurse to ensure that they were cleared to leave. Each of the pieces of the ensemble were again individually weighed and then weighed all together to measure their total sweat loss. The full protocol checklist that was followed can be found in Appendix E. Core temperature response, skin temperature response, and heart rate response throughout the test were recorded for each of the subjects. In addition, sweat loss values and accumulation values were calculated from the body weights.

Table 5.3: Physiological Wear Trial Protocol

Test Period	Duration	Activity
1	10	Rest period- seated with no gloves; subjective responses and reaction time test
2	50	Enter environmental chamber set to 34°C, 30% RH, radiant load: ~250 W/m^2, 1 m/s wind speed; walking on treadmill at 3 mph and a pre-determined grade to reach ~5 METS
3	10	Rest period (removal of gloves in chamber)- 1 minute of specific stretches; subjective responses and reaction time test; hydration (all while standing)
4	50	Walk on treadmill at 3 mph and a pre-determined grade to reach ~5 METS
5	10	Rest period (removal of gloves in chamber)- 1 minute of specific stretches; subjective responses and reaction time test
6	10	Rest period (outside of chamber)- seated with no gloves; subjective responses and reaction time test
		Post-test

Figure 5.4: Chamber Set Up for Physiological Wear Trial

5.3 Physiological Wear Trial Results

All of the subjects' core temperatures were averaged for each of the suits and the rise in core temperature was plotted over time in Figure 5.5. The rest periods inside and outside the chamber as well as the walk periods are indicated.

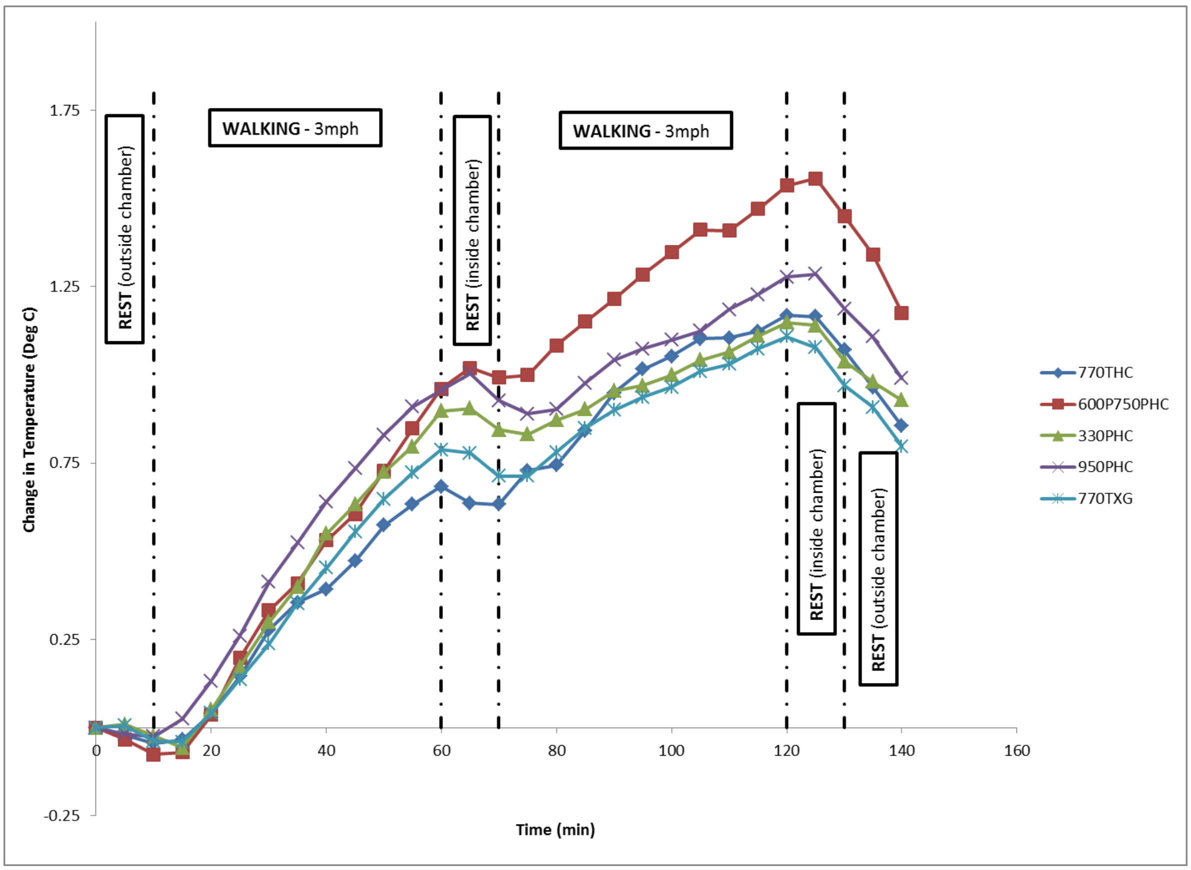


Figure 5.5: Change in Core Temperature during the Physiological Wear Trial

The changes in heart rate over time, shown in Figure 5.6, and the change in physiological strain index over time, shown in Figure 5.7, were also plotted in the same way. The heart rate plot does not start at zero because the minimum heart rate recorded for each of the subject over the entire time that their heart rate was recorded was used as the reference value.

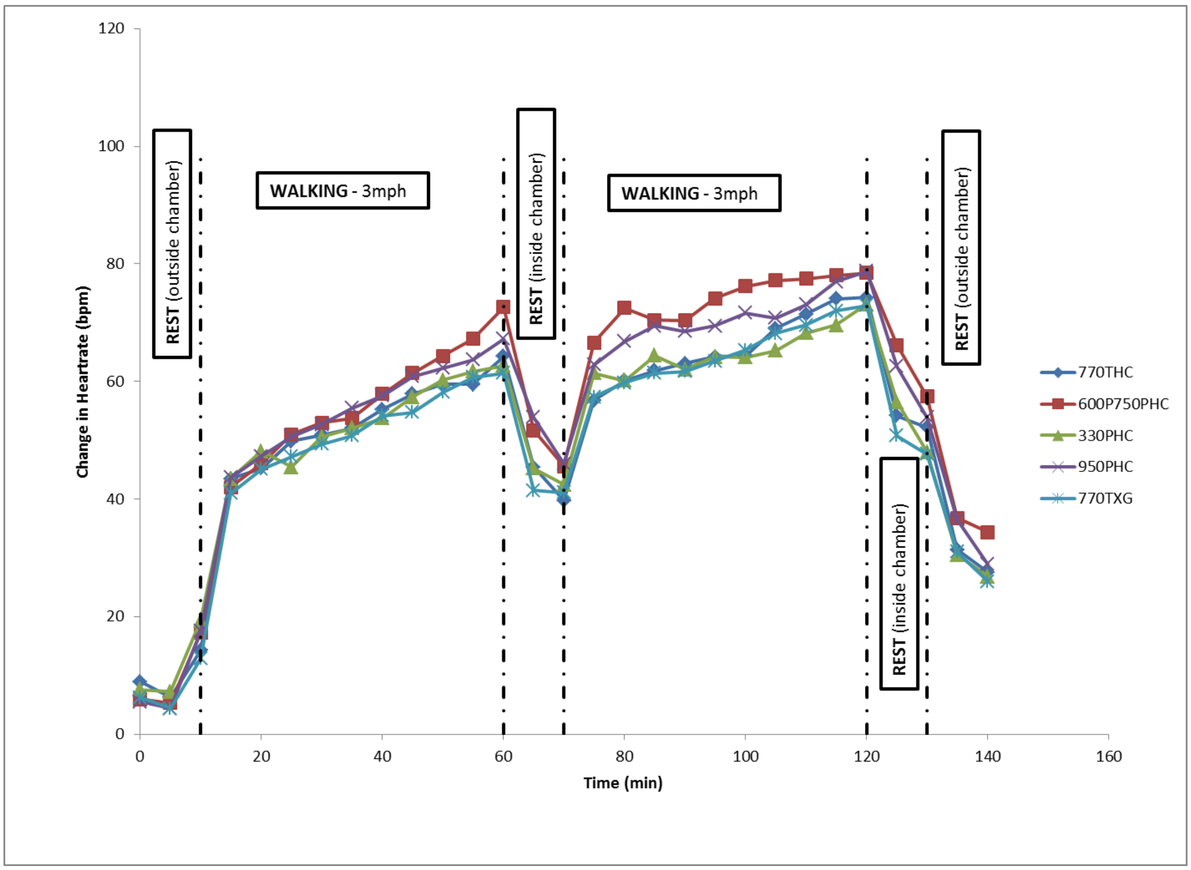


Figure 5.6: Change in Heart Rate during the Physiological Wear Trial

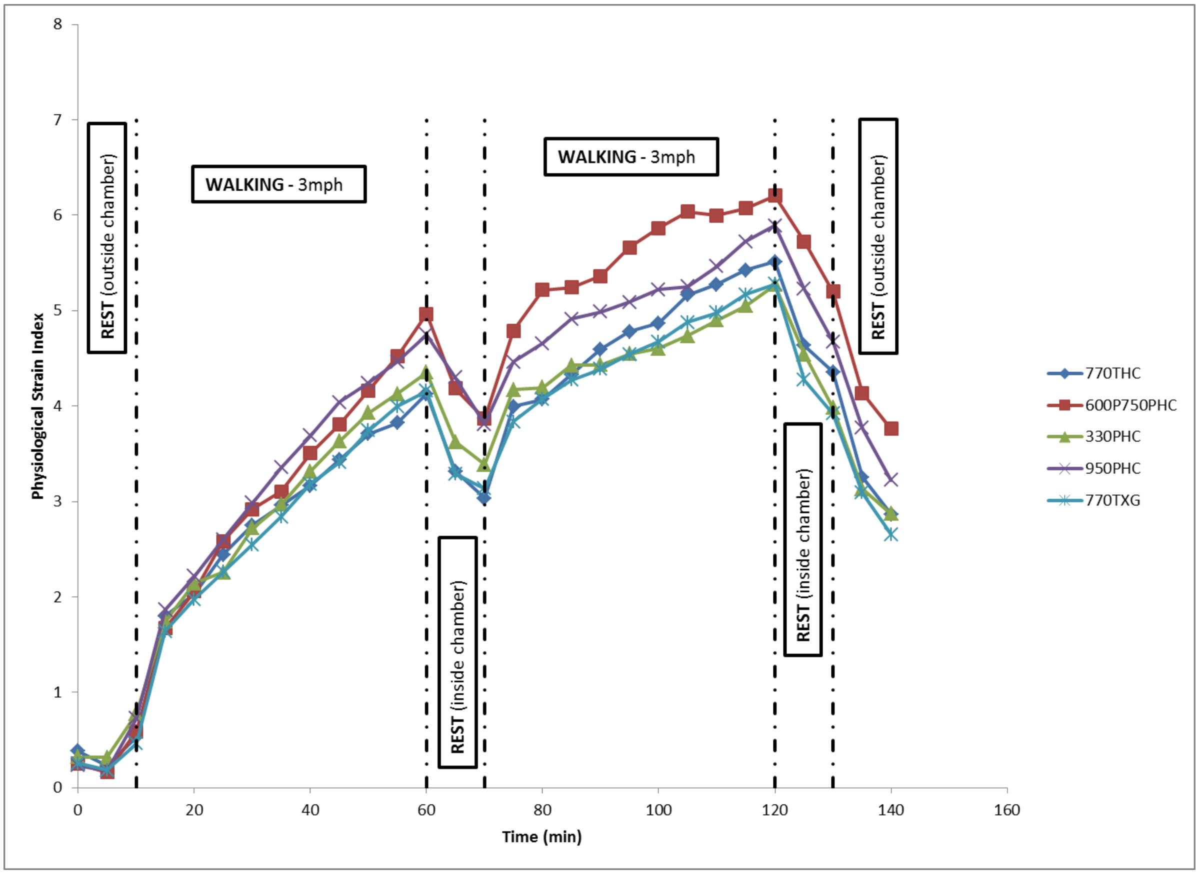


Figure 5.7: Change in Physiological Strain Index during the Physiological Wear Trial

The individual skin temperatures of the chest, back, thigh, and the forearm of each of the subjects were averaged together and then averaged with the other subjects for each suit to get the average change in overall skin temperature. It was then plotted the same way as core temperature, heart rate, and physiological strain index (Figure 5.8). The change in the individual skin temperatures (chest, back, forearm, and thigh) was also plotted (5.9-5.12).

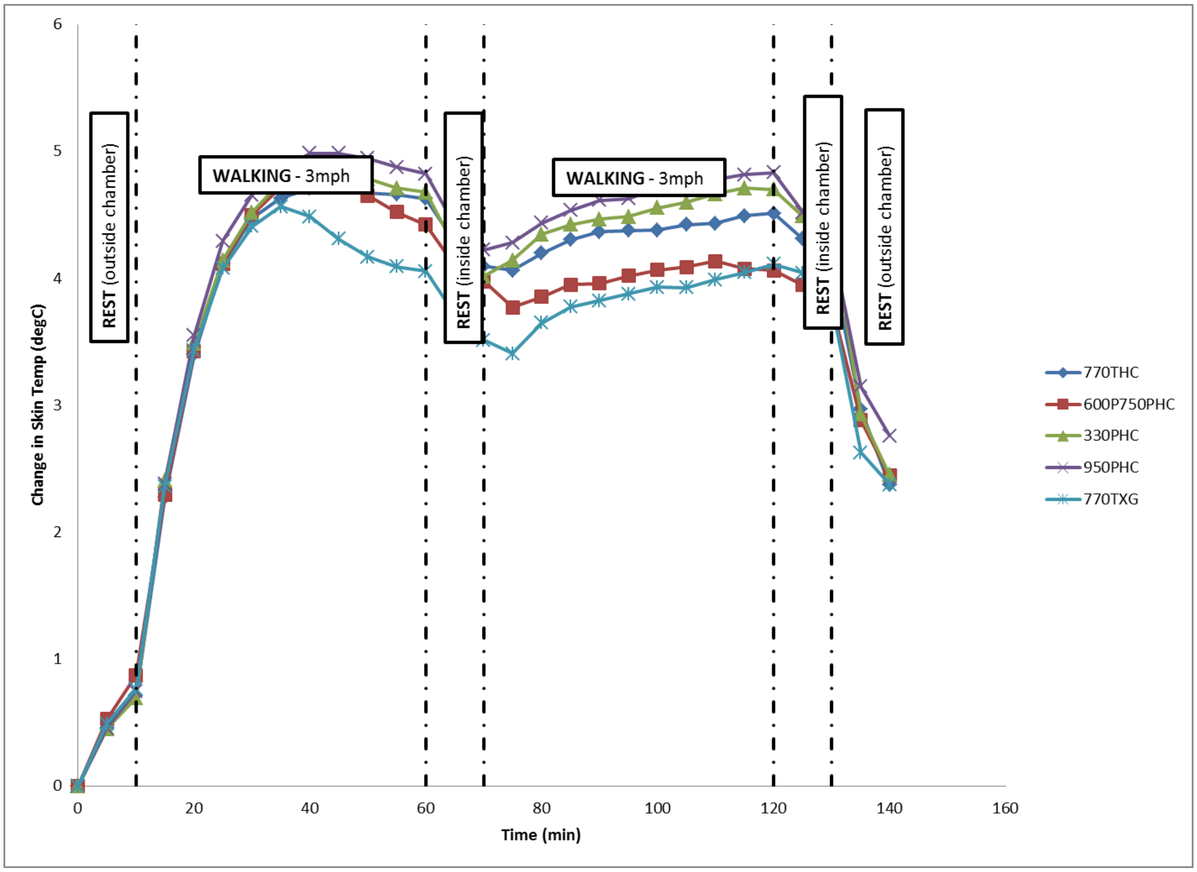


Figure 5.8: Average Change in Overall Skin Temperature during the Physiological Wear Trial

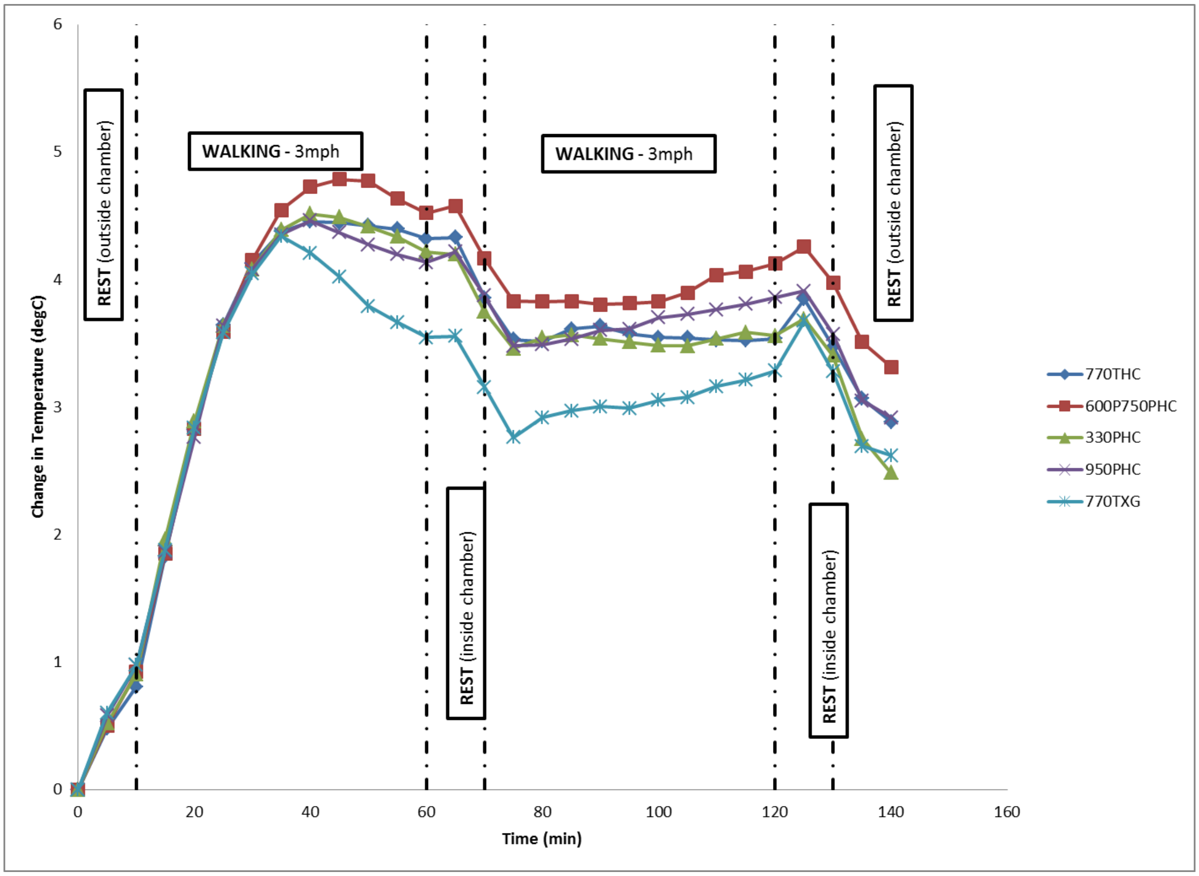


Figure 5.9: Average Change in Chest Skin Temperature during the Physiological Wear Trial

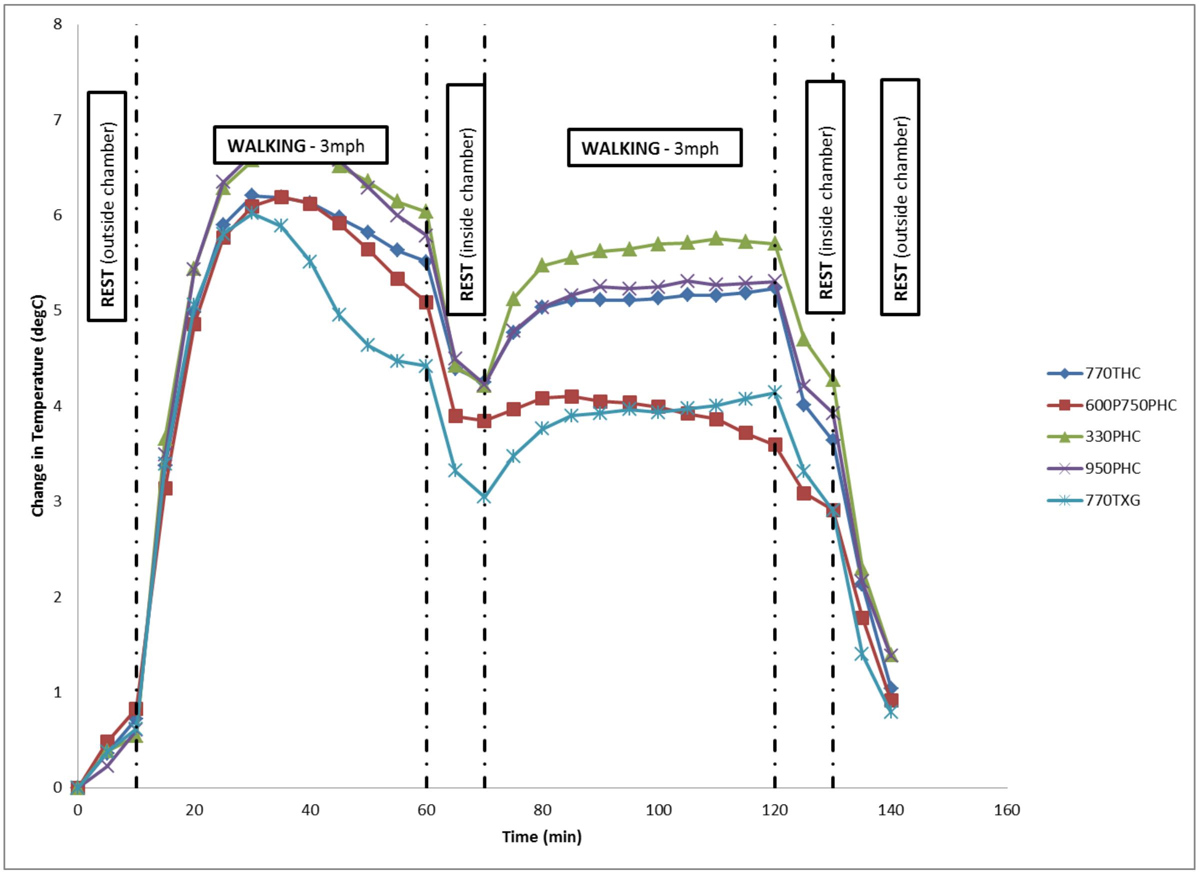


Figure 5.10: Average Change in Back Skin Temperature during the Physiological Wear Trial

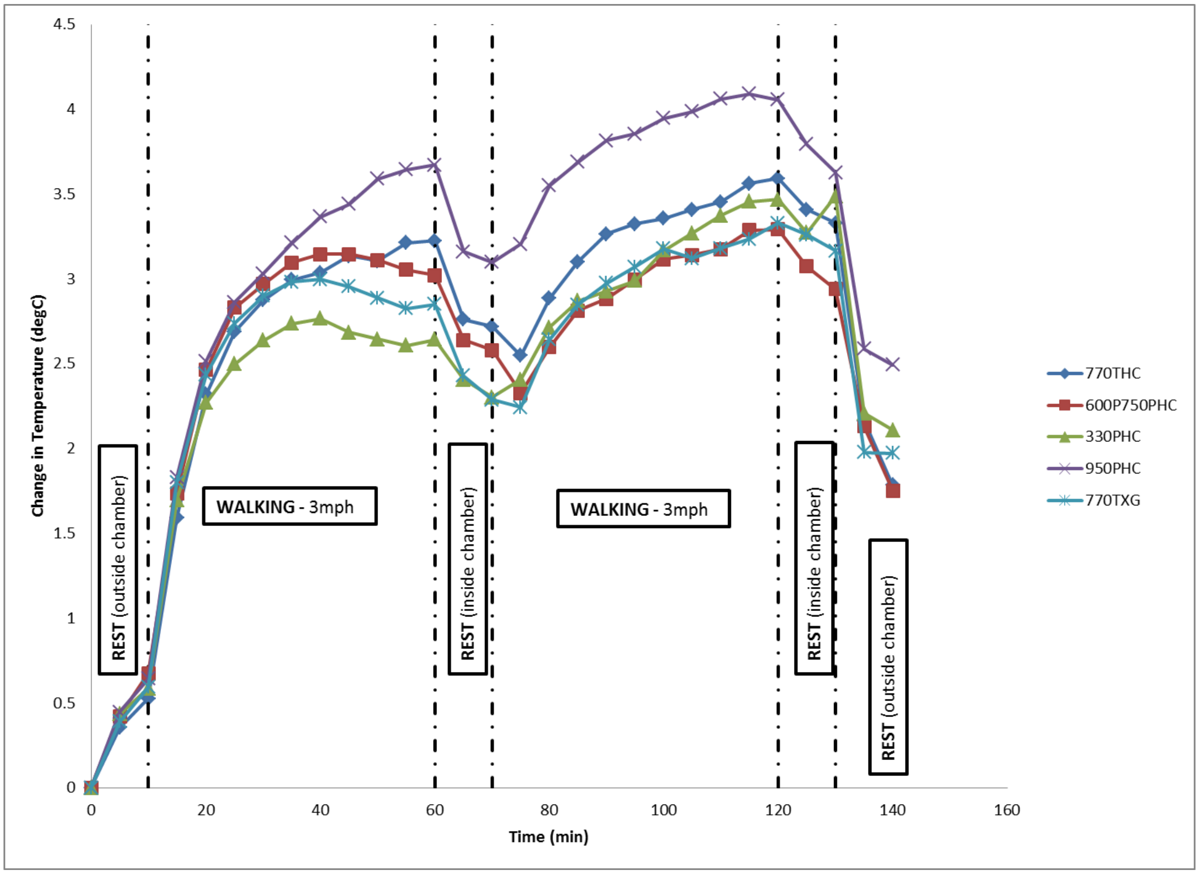


Figure 5.11: Average Change in Forearm Skin Temperature during the Physiological Wear Trial

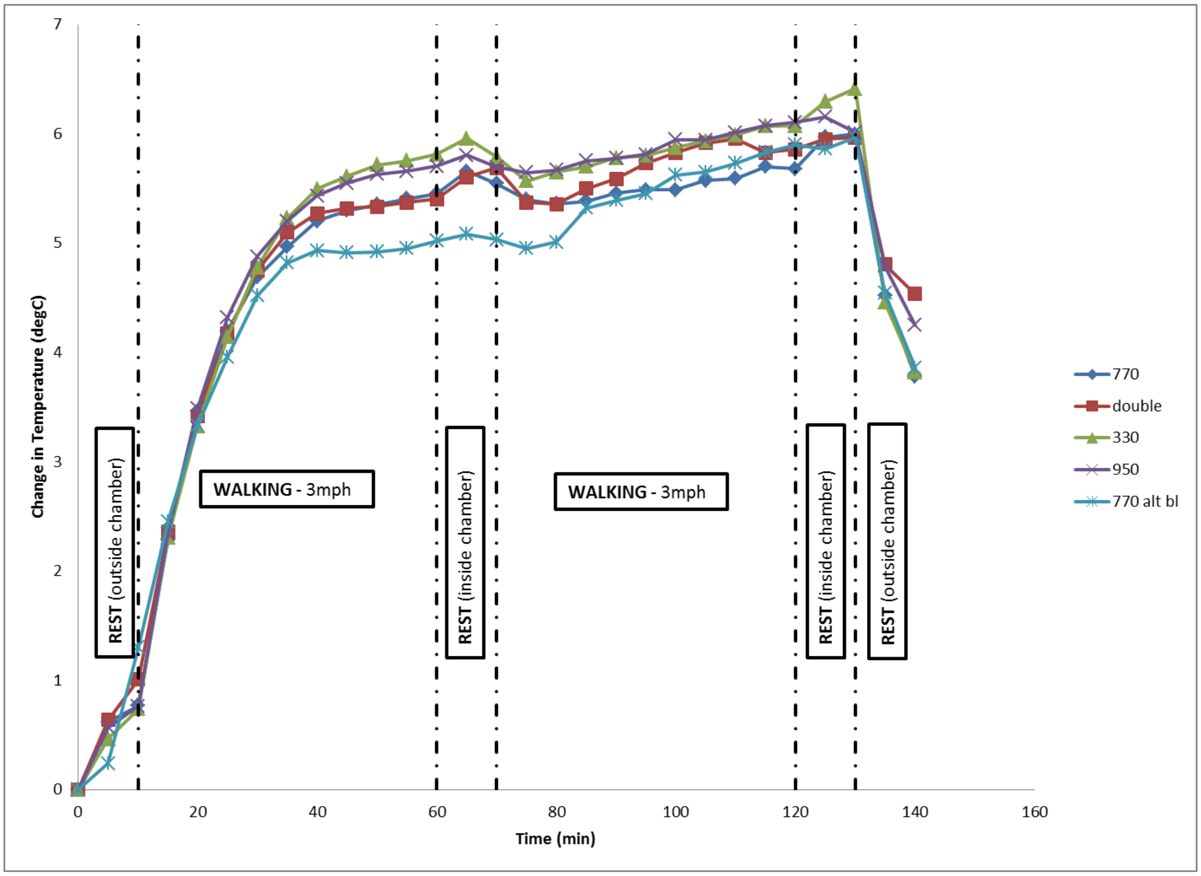


Figure 5.12: Average Change in Thigh Skin Temperature during the Physiological Wear Trial

The average total weight loss of the subjects for each garment, taking into account water intake and weight loss from urine, is shown in Figure 5.13. The average ensemble weight gain for each of the garments is shown in Figure 5.14. Finally, the average weight gain of the jacket and pants alone for each of the garments is shown in Figure 5.15.

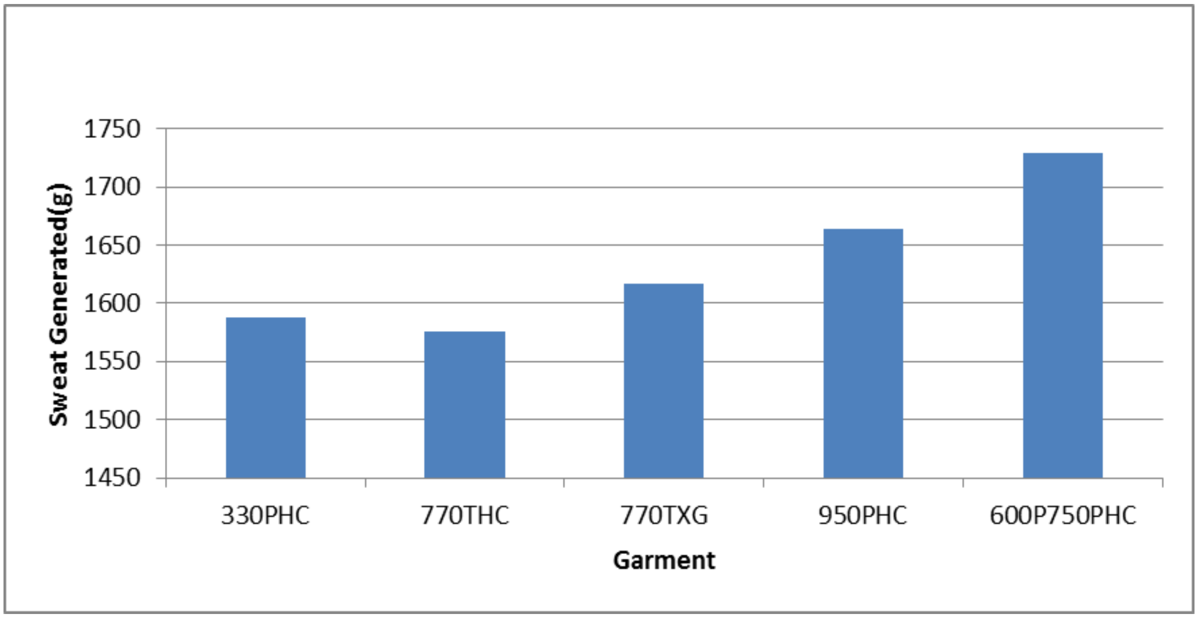


Figure 5.13: Average Total Human Subject Weight Loss for the Physiological Wear Trial

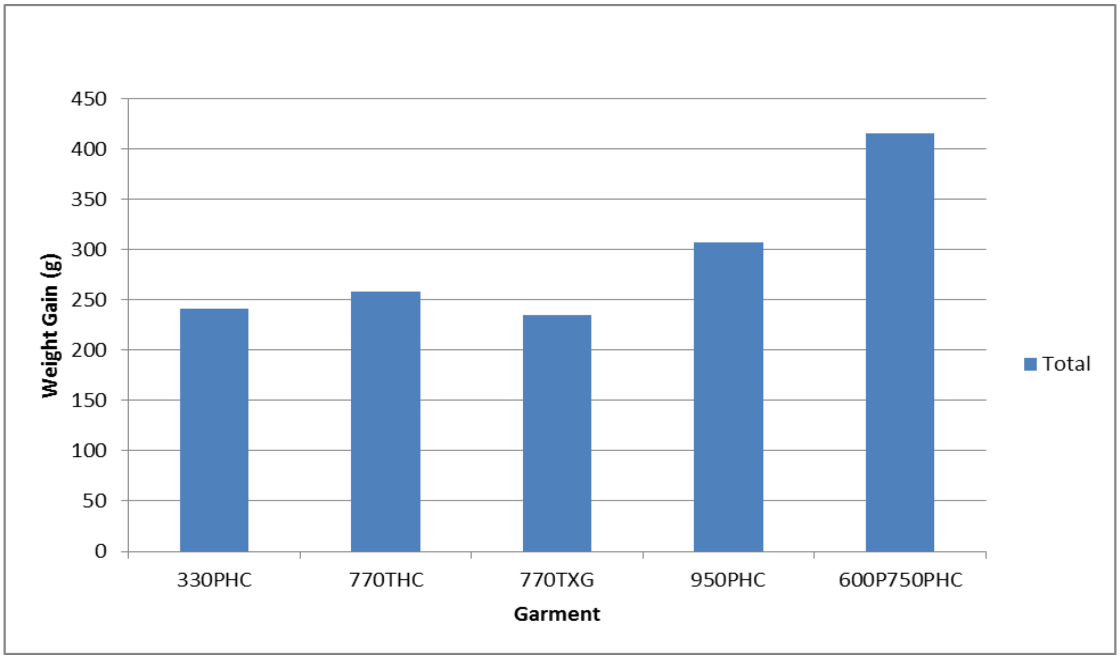


Figure 5.14: Average Ensemble Weight Gain (includes Garment, Shoes, Socks, Boxer Briefs, T-shirt, Gloves, Helmet, and Belt)

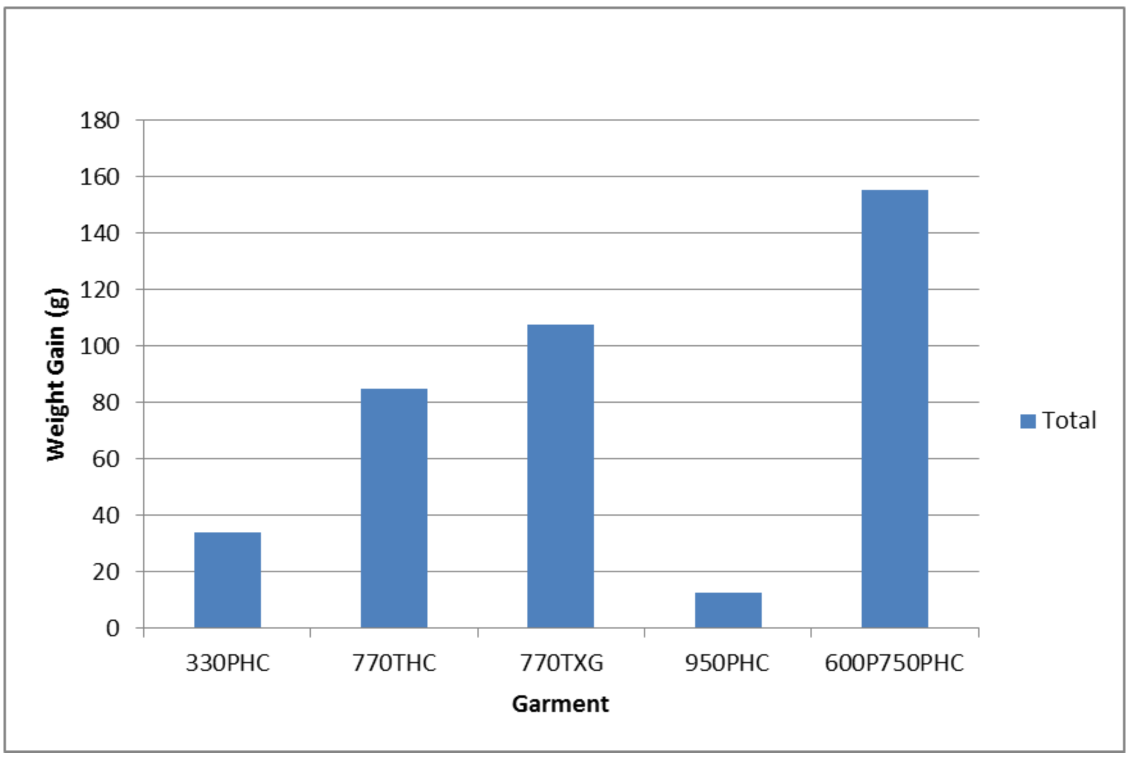


Figure 5.15: Average Jacket and Pants Weight Gain

5.4 Discussion of Physiological Wear Trial Results

Overall, the core temperature in Figure 5.5 rises throughout the duration of the wear trial. All of the garments follow this trend and there is only a slight, temporary drop during the rest periods. The rise in core temperature is expected because the subjects are working at a high work rate in a hot environment so, regardless of what they are wearing, there would be an expected increase in core temperature. In the first work period the heaviest single layer garment, 950PHC, has the highest rise in core temperature. It is significantly higher than all of the other suits at 30 minutes, shown in Table 5.4. This is not likely due to the weight or thickness alone since the double layer is a heavier suit. It could have something to do with the water repellent finish, the fact that it is black and may absorb heat faster from the radiant load, because it is stiffer, creating more resistance to walking, or a combination of these. The subjects noticed this difference as indicated by one of the comments in the subjective survey stating that "in the first portion of this segment, my [back] was notably hotter while the garment was still dry and while my [t-shirt] especially was still dry."

Table 5.4: Differences of Garments in Change in Core Temperature at 30 min

Garments	770THC	770TXG	950PHC	600P750PHC
330PHC	NS	NS	*	NS
770THC		NS	**	NS
770TXG			*	NS
950PHC				*

NS non-significant, * significant at the 90% level, ** significant at the 95% level, *** significant at the 99% level

During the first rest period, the core temperature rise of both of the 7.7 oz/yd^2 twill garments (770THC and 770TXG) is lower than the other garments. The 7.7 oz/yd^2 twill with the heavy cotton base layer is significantly lower than the double layer suit and the heaviest single layer plain weave. The 7.7 oz/yd^2 with the wicking FR base layer is significantly lower than the double layered system. Finally, during the last rest period in the chamber where you see the maximum rise in core temperature for the garment, the rise in core temperature for the double layer suit is significantly higher than every other suit. Table 5.5 shows these differences.

Table 5.5: Differences of Garments in Maximum Change in Core Temperature

Garments	770THC	770TXG	950PHC	600P750PHC
330PHC	NS	NS	NS	**
770THC		NS	NS	**
770TXG			NS	**
950PHC				**
NS non-significant, * significant at the 90% level, ** significant at the 95% level, *** significant at the 99% level				

For the heart rate, there are no large differences between the garments because heart rate is variable from person to person. However the lightest suit is significantly lower than the double at the max rise. This could be due to a slightly elevated work rate owed to the increased work involved with exercising in a heavier, stiffer garment. The physiological strain index, which combines the effects of the heart rate and the core temperature shows the same trend that is seen in the core temperature graph. At the max rise in physiological strain index during the last rest period in the chamber, the double layer suit is significantly higher than all of the suits except for the heaviest single layer suit.

The overall skin temperature remains fairly constant over time for all of the suits with a slight drop in the middle of the first work period. This may be explained by the subjects starting to sweat and therefore dissipating more heat through the evaporation of sweat or garments and base layers accumulating moisture and aiding in evaporation of sweat. The lightest weight garment has the second highest rise in skin temperature during the second work period. This is because the heat from outside of the body overtakes the amount of metabolic heat being produced. This partly explains why the core temperature of the lightest suit is not significantly lower than the other suits. However, the THL values did not predict that the lightest garment would perform much better than the others in the sweating hot plate or sweating manikin testing. It would be interesting to see how the lightweight suit would affect core temperature when no radiant load is present. The chest skin temperature represents what would be seen during wildland firefighting away from a radiant load such as the fire or the sun. Specifically, it also shows an area where the base layer has a significant influence on the skin temperature. The 7.7 oz/yd^2 twill suit with the modacrylic/FR rayon blend base layer has a significantly lower temperature than most of the garments throughout the wear trial as shown in Tables 5.6 and 5.7. The subjective data showed that the subjects felt this difference when one stated that the twill garment with the alternate base layer “didn’t seem to make [him] as hot.”

Table 5.6: Differences of Garments in Change in Chest Skin Temperature at 65 min

Garments	770THC	770TXG	950PHC	600P750PHC
330PHC	NS	*	NS	NS
770THC		NS	NS	NS
770TXG			*	***
950PHC				NS

NS non-significant, * significant at the 90% level, ** significant at the 95% level, *** significant at the 99% level

Table 5.7: Differences of Garments in Change in Chest Skin Temperature at 120 min

Garments	770THC	770TXG	950PHC	600P750PHC
330PHC	NS	NS	NS	NS
770THC		NS	NS	NS
770TXG			NS	***
950PHC				NS

NS non-significant, * significant at the 90% level, ** significant at the 95% level, *** significant at the 99% level

The back skin temperature is representative of the environment that would be experienced when there is a radiant load present in the areas of the body with a base layer because of the positioning of the radiant lamps behind the subjects. During the second work period, the lightest plain weave had the highest skin temperature, particularly higher than the twill garment with the modacrylic/FR rayon blend base layer and the double layer garment. The subjects indicated that they felt “a lot of heat on [their] back” during the work periods. In the presence of a radiant heat load, a very light garment can have a negative impact because the proper balance between radiant protection and the ability to release heat through sweat evaporation is not ideal. The double layer garment has a lower skin temperature than most of the other garments because it is able to protect from the radiant load well. However, even though the skin may heat up slower since it is protected from the external radiant source, because the body cannot easily release the metabolic heat generated, the double layer system still poses more of a threat to the wearer to develop heat stress. The biggest difference at 120 minutes, however, is seen between the heaviest single layer garment and the twill fabric with the modacrylic/FR rayon blend base layer. Table 5.8 shows these differences.

Table 5.8: Differences of Garments in Change in Back Skin Temperature at 120

Garments	770THC	770TXG	950PHC	600P750PHC
330PHC	NS	*	NS	*
770THC		NS	NS	*
770TXG			***	NS
950PHC				*
NS non-significant, * significant at the 90% level, ** significant at the 95% level, *** significant at the 99% level				

The forearm skin temperature represents an area with no base layer. In this area the heaviest single layer garment has a Shelltite™ finish causing it to repel water. This stops the garment from wicking sweat from the skin, mitigating evaporation, and making the skin stay hotter than every other garment. The subjects indicate that the heavy single layer garment was “hot pretty quick,” “does not absorb sweat,” and that they started “sweating pretty quick.” The fact that they felt they were “sweating pretty quick” might be due to the fact that the garment did not absorb sweat readily, causing a wet skin sensation, so they may have noticed sweating more and sooner rather than actually beginning to sweat more or sooner. The double layer stays the coolest on the back, likely because it is continuing to protect from the radiant heat. All of the statistical analysis can be found in Appendix F.

The weight loss with each garment is indicative of the amount of sweat lost from the bodies of the subjects. The data shows that, for the most part, as the weight of the garments increased, the amount of sweat loss experienced increased. The exception to this trend was the lightest garment. As discussed with the skin temperature, the light weight garment made the skin of the subjects very hot which likely caused them to generate more sweat than would be expected. The general trend of the ensemble weight gain shows that with the increase in weight of the fabric, there is an increase in ensemble weight gain with the exception of the modacrylic/FR rayon blend base layer. This follows closely with the sweat loss data. However, when you look at the weight gain of just the jacket and pants, they follow that trend except for the heaviest plain weave garment (950PHC). This is because there is a water repellant finish on this garment allowing for less sweat to be held in the garment. This effect is masked in the graph showing the total ensemble weight gain because there are many other parts of the garment that can make up for the loss of sweat pickup by the 9.5 oz/yd^2 garment.

The reaction time data has been omitted from the results section because it did not show any trends. However it can be found in Appendix G. The lack of a distinguishing trend is likely because of a combination of issues with the software and equipment being used during testing and a lack focus by the subjects during testing. It could also be because the task that they were required to do was so simple that it would not show any differences due to fatigue. Finally, a less likely reason for the lack of trends is that there is no effect of fatigue and core temperature on cognitive results.

5.4.1 Correlations between Measured Heat Loss and Physiological Response

Correlation analyses were calculated using the data from the wear trial and results from the sweating hot plate and sweating manikin measures of fabric and clothing heat loss (Table 5.9). Each of the dependent variables was plotted against each of the independent variables and the correlation values were used to see which independent variable predicted the dependent variables the best.

Table 5.9: Correlations done between Wear Trial Results and Instrumentation Results

Dependent Variables	Independent Variables
Max Core Temp Rise	THL
Max HR Rise	1/THL
Chest Skin Temp Rise 120 min	Evaporative Component of THL
Back Skin Temp Rise 120 min	Weight
Sweat Loss	Thickness
Ensemble Weight Gain	Manikin THL
Jacket and Pants Weight Gain	1/Manikin THL

All of the correlations can be found in Appendix H. 1/THL showed to be the best predictor of the maximum rise in core temperature. The correlation graph in Figure 5.16 shows the R^2 value to be 0.9661. This is a strong correlation but would only be accurate when all garments have the same design and the same base layer worn with it. Figure 5.17 shows the correlation between the THL and the maximum rise in core temperature. The relationship is not as strong in this correlation but THL is still shown to be a good predictor of the physiological response.

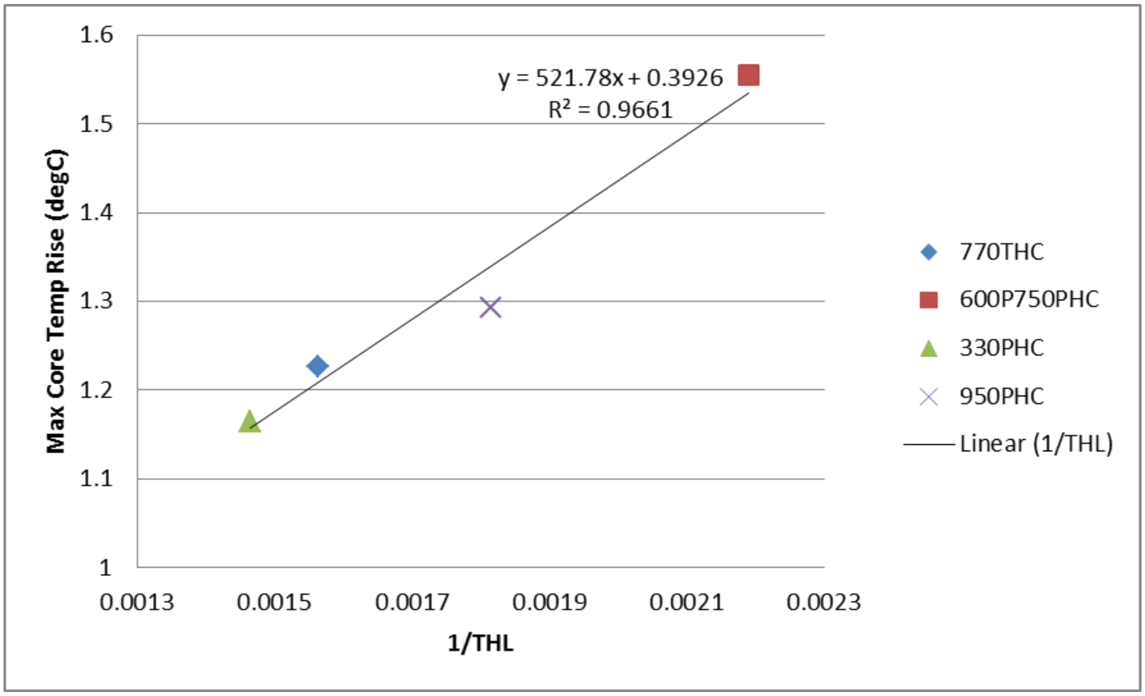


Figure 5.16: Correlation between the Maximum Rise in Core Temperature and 1/Plate THL

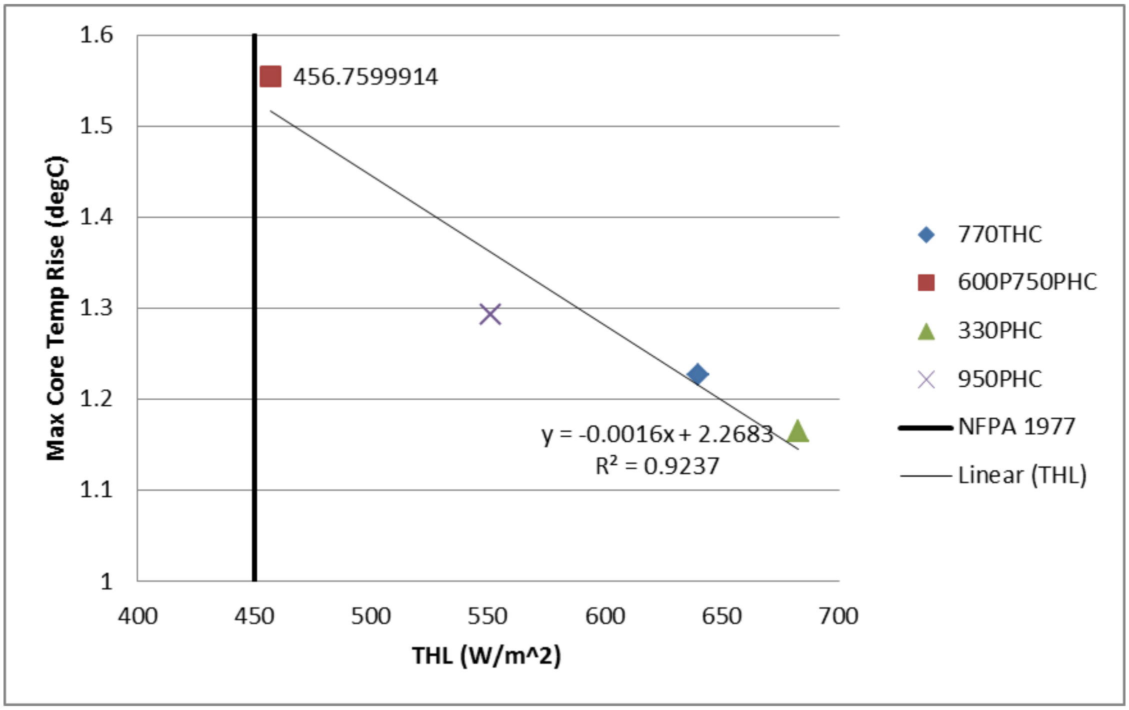


Figure 5.17: Correlation between the Maximum Rise in Core Temperature and Plate THL

The correlation between the maximum rise in core temperature and 1/ Manikin THL, shown in Figure 5.18, has a direct comparison to the garments because the manikin was dressed in the same way that the subjects in the wear trial was dressed. In addition, the fabrics are able to be tested in human form and therefore can take into account layers and air gaps in the clothing. Because of this one might expect that there would be a higher correlation between the manikin THL and the physiological response than between the plate THL and the physiological response. However, this was not seen in this data. This could be because there was a lot of variability with the sweating manikin garments. The sweating hot plate is inherently less variable than the sweating manikin because there are no air layers and accessories on different body parts. The sweating manikin has differing amounts of exposure due to accessories and this, along with the air layers, can wash out differences between the garments. In addition, the sweating manikin has traditionally been shown to be a better predictor of physiological response in studies with structural turnout gear[44]. These suits are multilayer systems that include a semi-permeable moisture barrier. The moisture barrier is the primary barrier to sweat evaporation. The different transport mechanisms of moisture across this semi-permeable membrane versus a fabric structure as well as the complex transfer mechanisms associated with a multi-layer system may come into play when considering differences of how moisture evaporation takes place across a composite on a flat plate versus a realistic wear configuration[44]. Table 5.10 shows all of the correlations with maximum core temperature rise as a dependent variable. The values shown in red cannot be considered a direct comparison because they were done on the plate without the base layers. 1/THL is highlighted indicating that it is the best correlation.

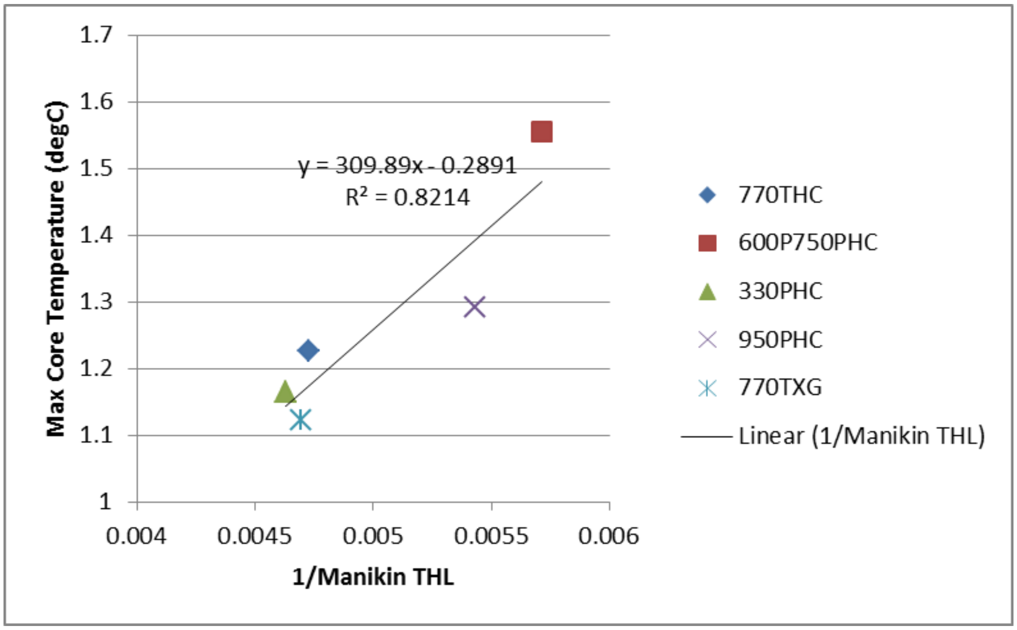


Figure 5.18: Correlation between the Maximum Rise in Core Temperature and 1/Manikin THL

Table 5.10: Correlation Values with Instrumentation and the Maximum Rise in Core Temperature

Dependent Variable	Independent Variable	R^2 value
Max Core Temp Rise	THL	0.9237
	1/THL	0.9661
	Evap Comp of THL	0.8304
	Weight	0.874
	Thickness	0.8165
	Manikin THL	0.8005
	1/ Manikin THL	0.8214

The skin temperature was also correlated with the instrumentation. However, the only notable correlation was between the chest skin temperature rise at 120 minutes and the evaporative component of THL, as indicated by Table 5.11. Figure 5.19 shows this correlation. Both the correlations with the back and chest skin temperature at 120 minutes are included in the table, however the overall skin temperature and the forearm skin temperature have little correlation at all because they both show similar skin temperatures for all of the garments throughout the test. The forearm skin temperature shows a difference with the heavy water repellant plain weave but since this is the only garment that differs, it is not enough to show a correlation.

Table 5.11: Correlation Values with Instrumentation and the Skin Temperature for the Back and Chest at 120 minutes

Chest Skin Temp Rise 120 min	THL	0.6732
	1/THL	0.6691
	Evap Comp of THL	0.7492
	Weight	0.7125
	Thickness	0.4599
	Manikin THL	0.2001
	1/Manikin THL	0.1949
Back Skin Temp Rise 120 min	THL	0.6181
	1/THL	0.6114
	Evap Comp of THL	0.5255
	Weight	0.4223
	Thickness	0.5736
	Manikin THL	0.2395
	1/Manikin THL	0.2537

The max heart rate rise also shows no good correlations as seen in Table 5.12.

Table 5.12: Correlation Values with Instrumentation and the Maximum Rise in Heart Rate

Max HR Rise	THL	0.3301
	1/THL	0.4277
	Evap Comp of THL	0.2063
	Weight	0.3047
	Thickness	0.3453
	Manikin THL	0.2112
	1/Manikin THL	0.179

When examining sweating data from the wear trial, the strongest correlation is shown with the ensemble weight gain and 1/THL as shown in Figure 5.19. However, when looking at the correlation between the garment alone and 1/THL the correlation is poor as shown in Figure 5.20. The reason why the total heat loss correlates is because more trapped heat leads to more sweating and, therefore, more sweat accumulation in the overall ensemble. That explains why the sweat loss correlates well with 1/ THL as well (Figure 5.21). There is also a slight influence of the increased thickness of the garment, leading to the ability to hold more sweat. However, when you eliminate the other parts of the ensemble, garments that are not able to hold water do not gain as much weight as the other garments. The water repellant plain weave garment is an example of this effect because it gains much less weight and depresses the correlation. The sweat that cannot be held in the garment is still collected in other parts of the ensemble, such as the t-shirt, socks, and brief, allowing the ensemble weight gain to still give a good correlation.

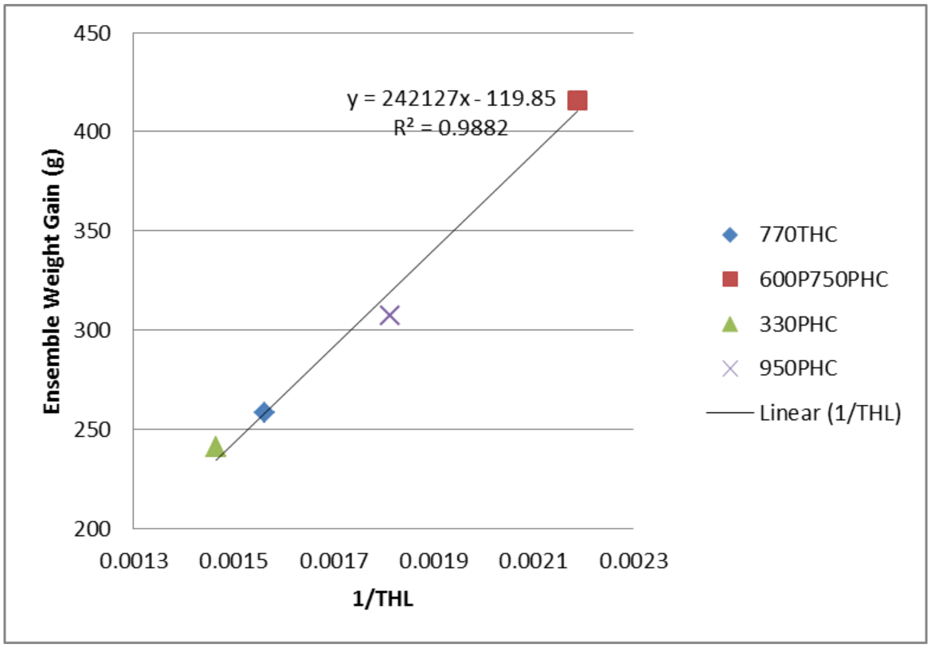


Figure 5.19: Correlation between the Ensemble Weight and 1/Plate THL

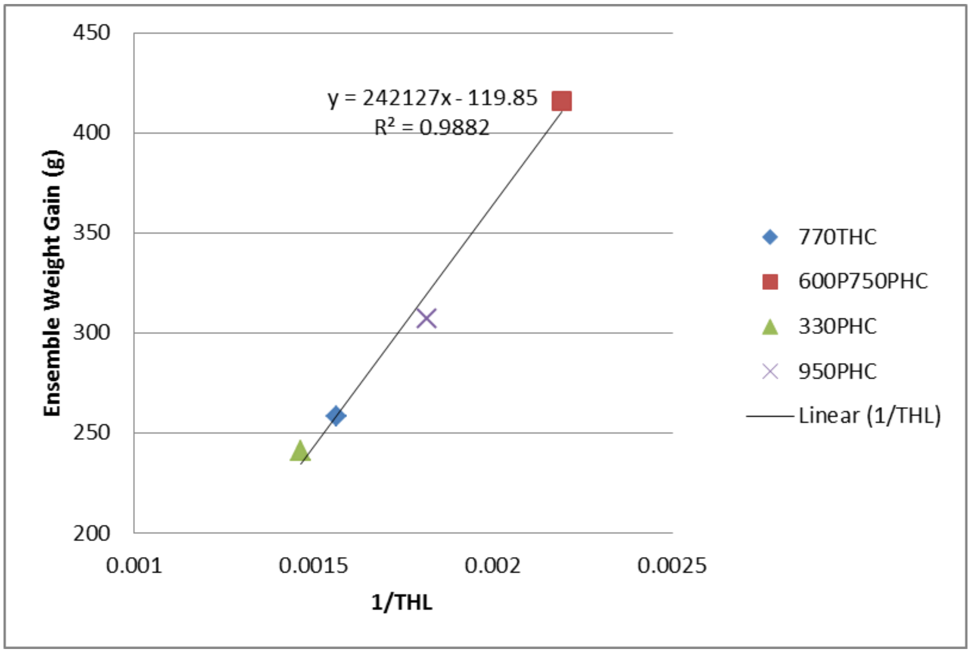


Figure 5.20: Correlation between the Garment (Jacket and Pants only) Weight Gain and 1/Plate THL

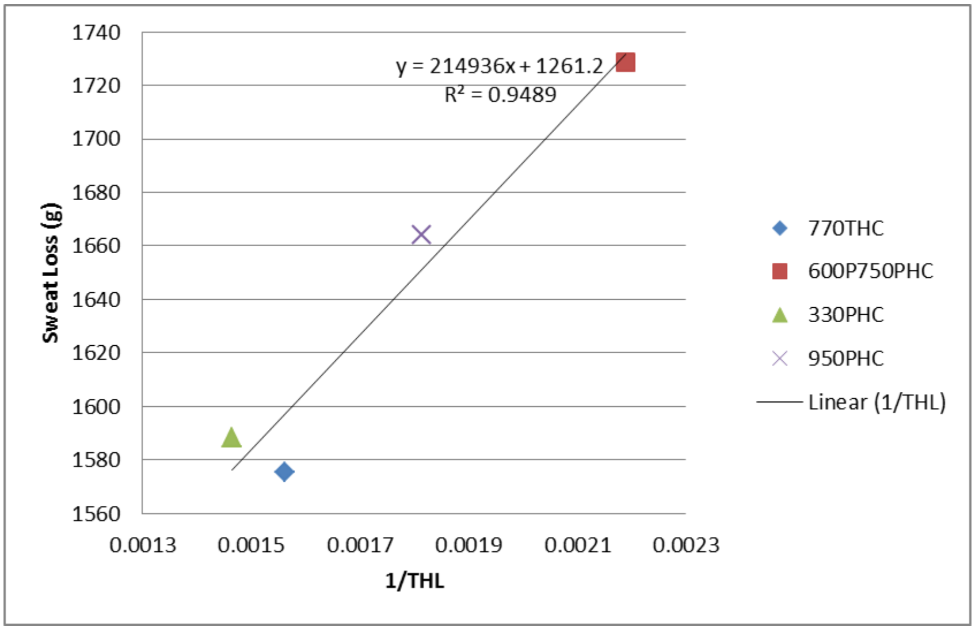


Figure 5.21: Correlation between the Sweat Loss and 1/Plate THL

Since the manikin did not show much difference between the garments, due to the variability, the correlations between the dependent variables and the manikin THL were not as strong as would be expected. The variability from the manikin came from the accessories that were consistent in the testing of all of the other garments. These accessories played a large role in the manikin THL and compressed the differences between the garments. Further investigation or repeat of some of the sweating manikin tests may be required to expand these differences. All of the correlations between the sweating data from the wear trial and the instrumentation can be seen in Table 5.13.

Table 5.13: Correlation Values with Instrumentation and the Sweating Data

Sweat Loss	THL	0.9399
	1/THL	0.9489
	Evap Comp of THL	0.9413
	Weight	0.7809
	Thickness	0.6187
	Manikin THL	0.8874
	1/Manikin THL	0.9012
Ensemble Weight Gain	THL	0.9541
	1/THL	0.9882
	Evap Comp of THL	0.8835
	Weight	0.875
	Thickness	0.7831
	Manikin THL	0.86
	1/Manikin THL	0.8801
Jacket and Pants Weight Gain	THL	0.3727
	1/THL	0.4465
	Evap Comp of THL	0.2359
	Weight	0.4402
	Thickness	0.5506
	Manikin THL	0.0665
	1/Manikin THL	0.0775

5.4.2 Predictions using THL and 1/THL

A recommended minimum THL value for structural turnout gear was established by using the THL value predicted in a study that evaluated the predictive capabilities of the Total Heat Loss Test for structural firefighting garments[65]. In this study, they measured the physiological effects of seven different structural firefighting garments ranging in their THL values from 96.5 to 439 W/m^2. Using the results they obtained from the physiological study and the THL values, they established a linear correlation between physiological response with THL and a hyperbolic correlation between the physiological responses with 1/THL (inverse relationship). These relationships cross at two points as shown in Figure 5.22[65]. As the total heat loss of the system approaches zero, there would be a dramatic increase in the physiological response that would not be accounted for by the linear relationship. However, the hyperbolic relationship is able to show this trend. As the total heat loss value of a garment gets very high, the garment no longer has a real impact on the physiological response, also indicated by the hyperbolic relationship but once again no longer following the linear relationship. [65] The intersection point indicated shows where a minimum THL value could be justified because at this point there is no longer as great of an increased benefit by increasing the THL value. This is considered to be the breakpoint value. Lower than this value on the linear relationship has benefits greater than the line implies. Values higher on the linear relationship than the breakpoint value imply that benefits are greater than they actually are. The predicted THL and the inverse of the predicted THL were used to plot a hyperbolic prediction for structural firefighting turnout gear to determine the breakpoint value[65]. The lowest point on this hyperbola was the minimum THL. The minimum THL from this study was used as the justification for the current THL value required by NFPA 1971: Standard on Protective Ensembles for Structural Fire Fighting and Proximity Fire Fighting[66], [67]. The same methodology used in that study was used to find a recommended minimum THL value from the physiological responses for wildland firefighting gear in this study compared to the THL values measured for each of the garments in the wear trial. The hyperbola and the corresponding minimum THL, found using this methodology are indicated in Figure 5.23. The breakpoint value is predicted to be at 565 W/m^2.

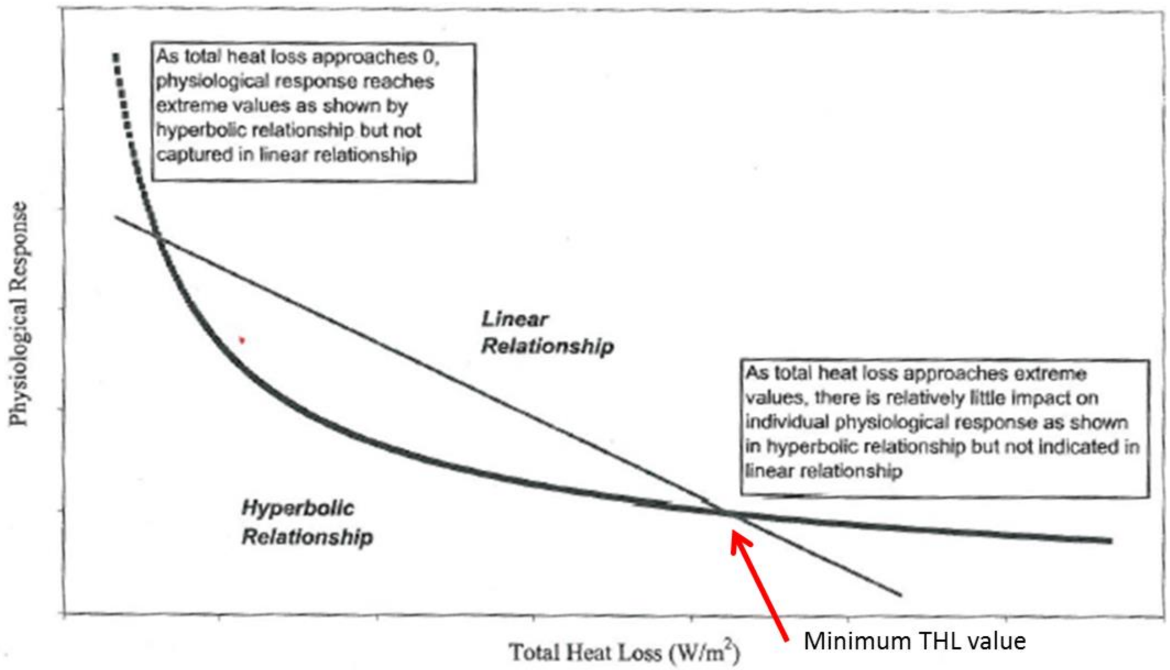


Figure 5.22: Hypothetical Relationship between Total Heat Loss and Physiological Response (based on total heat loss extremes)[65]

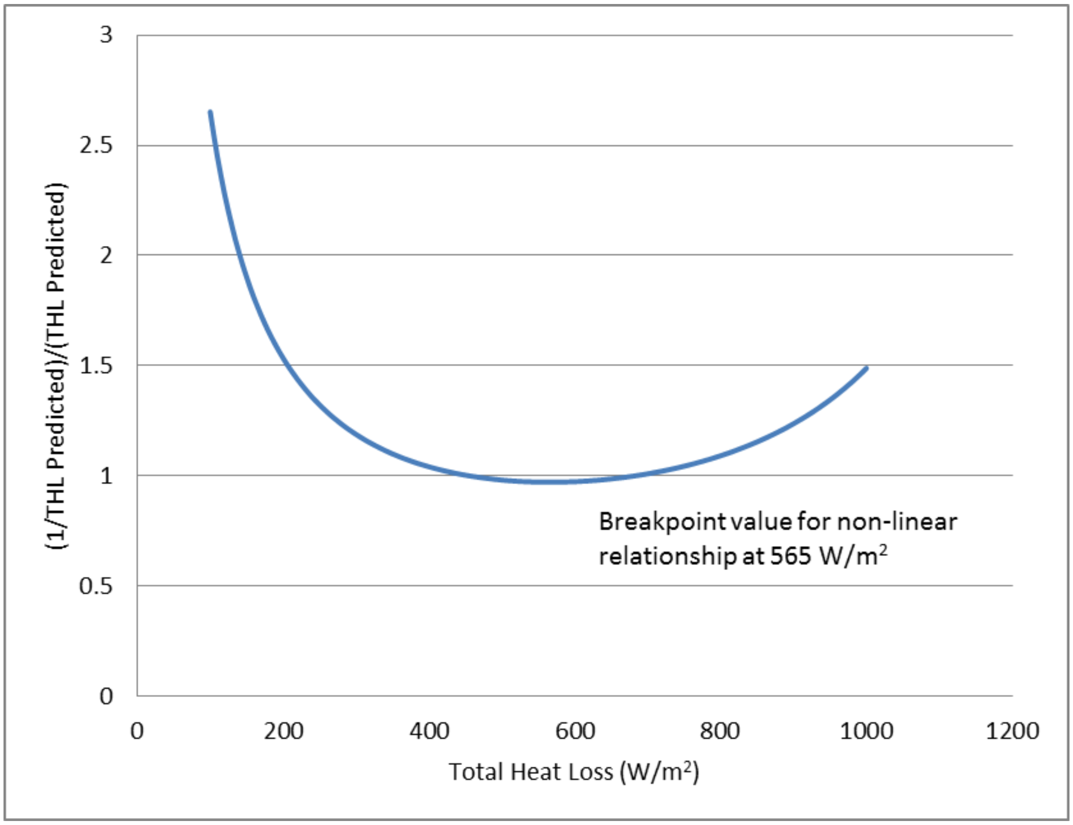


Figure 5.23: Differences in Predictions Using 1/THL and THL for Wear Trial

6 Non Traditional Measurements of Heat Stress

6.1 Physiological Manikin Testing

6.1.1 Materials

The garments used on the physiological manikin were the same as those used in the wear trial. From the fabric tested on the sweating hot plate, one garment was made from the 330P, 950P, and 600P750P double layer configurations to be tested with the 7.1 oz/yd^2 cotton base layer (HC). These garments were selected because they represented a range of THL values and weights. In addition, two garments were made from the 770T material; one to be tested with the 7.1 oz/yd^2 cotton base layer (HC) and one to be tested with the 5.2 oz/yd^2 modacrylic/FR rayon blend base layer (XG). This allowed for a physiological comparison between two of the base layers. Like the sweating manikin, all of the garments were tested with the same gloves, socks, underwear, belt, and athletic shoes. The helmet however, though it was the same type, had to have a bigger hole drilled into it to fit the physiological manikin. The garments are summarized in Table 6.1.

Table 6.1: Garments Used in Physiological Manikin Testing

Garment	Base Layer	THL value (W/m^2)
3.3 oz/yd^2 Nomex® plain weave	7.1 oz/yd^2 cotton	683
7.7 oz/yd^2 Nomex® twill weave	7.1 oz/yd^2 cotton	640
“	5.2 oz/yd^2 modacrylic/ FR rayon blend	
9.5 oz/yd^2 Nomex® plain weave with a Shelltite™ water repellant finish	7.1 oz/yd^2 cotton	551
6.0 oz/yd^2 Nomex® plain weave and 7.5 oz/yd^2 Nomex® plain weave double layer system	7.1 oz/yd^2 cotton	457

6.1.2 Physiological Manikin Testing Protocol

The physiological manikin test was modeled to match the protocol used in the wear trial. The manikin was dressed in the garment being tested and then sat outside of the environmental chamber in the wheel chair to achieve thermoneutral, indicated when all of the body segments of the manikin are within the acceptable temperature range comparable to the skin temperature of a human. The test was then started with the activity level set at 1 MET and the activity type set at 0 to indicate that the manikin was sitting. At 10 minutes, the activity level was set to 5 METs and the activity type was set to 1 to indicate that the manikin was standing. In addition, the manikin was placed backwards on the manikin stand in the chamber so that the manikin's back could be exposed to the radiant source unobstructed, attached to the walking apparatus, and the walking apparatus was turned on to allow for movement of the manikin's legs. A picture of the setup can be seen in Figure 6.1. At 60 minutes, the activity level was set to 1.2 METs, the activity type remained at 1, and the walking apparatus was turned off. Over the next minute, the manikin was manually moved around, including the arms being placed above the head, elbow bends, and knee lifts. At 70 minutes, the activity level was set to 5 METs, the activity type remained at 1, and the walking apparatus was turned on. At 120 minutes, the activity level was set to 1.2 METs, the manikin stopped walking and the shoes were disconnected. For the next minute the manikin was manually moved around similarly to the previous rest period. Then at 130 minutes the test was ended and the wet clothes from the manikin test were weighed. The testing protocol is summarized in Table 6.2. A more detailed protocol can be found in Appendix I.

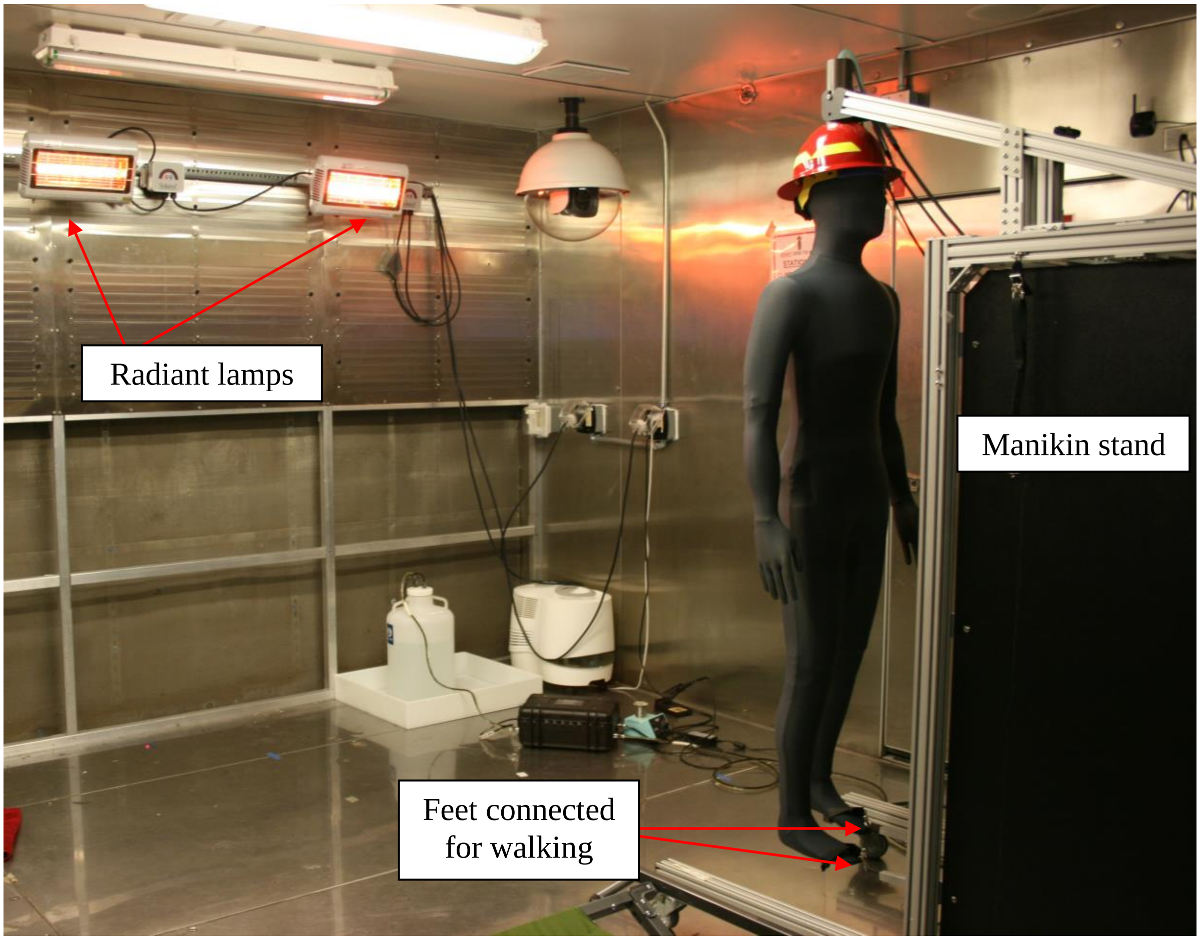


Figure 6.1: Physiological Manikin Testing Set Up

Table 6.2: Physiological Manikin Testing Protocol

Test Period	Time (min mark)	MET rate	Activity Type	Activity
1	0	1	0	Start test
2	10	5	1	Set manikin backwards on stand in chamber, hook shoes up for walking, turn manikin walking on
3	60	1.2	1	Stop walking, Move manikin around (arms above head, elbow bends, knee lifts)
4	70	5	1	Start walking
5	120	1.2	1	Stop walking and disconnect shoes, Move manikin around (arms above head, elbow bends, knee lifts)
6	130			End test, weigh clothing

6.1.3 Physiological Manikin Results

The core temperature of the physiological manikin over time with each garment, shown compared to the core temperatures in the wear trial in Figure 6.2, was plotted similarly to the wear trial data.

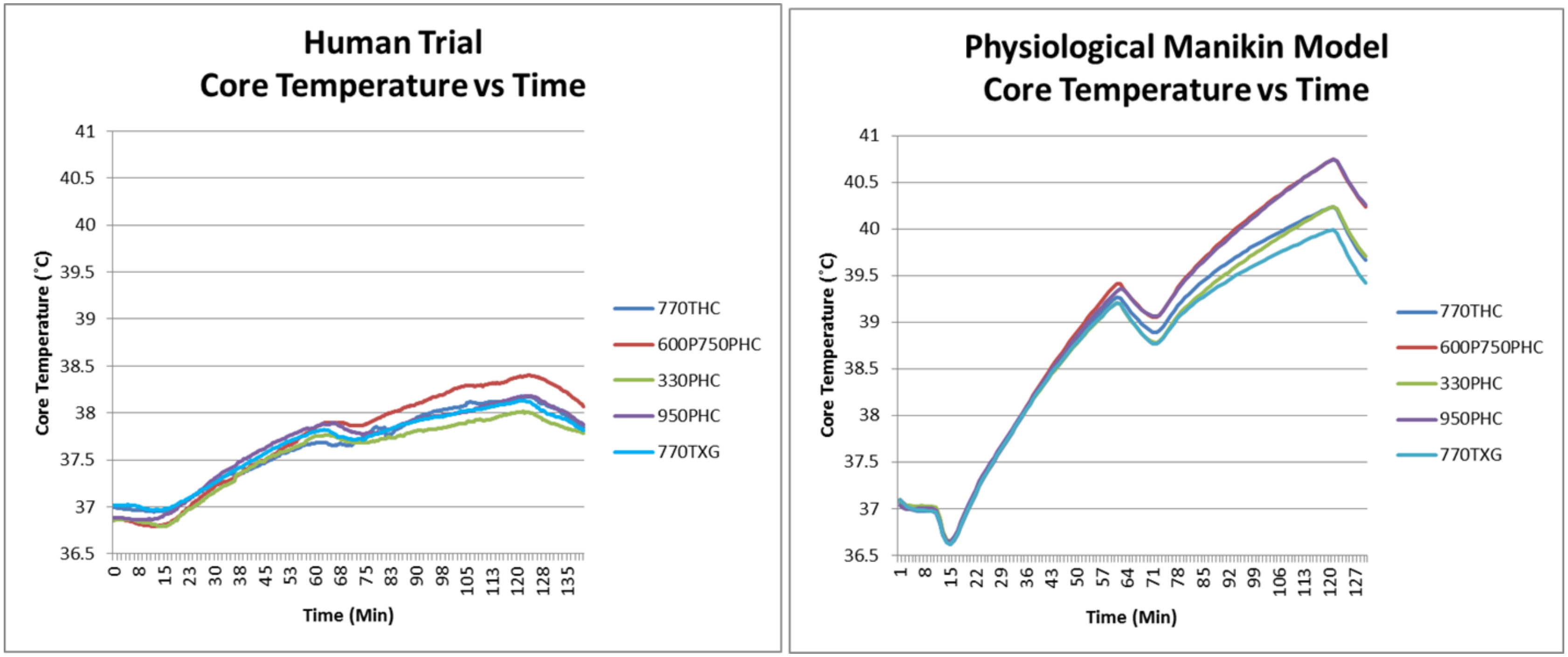


Figure 6.2: Core Temperature over Time from the Wear Trial compared to Core Temperature over Time from the Physiological Manikin

6.1.4 Physiological Manikin Discussion

The physiological manikin was run as a comparison to the physiological wear trial. When looking at the comparison between the core temperatures from the wear trial and the core temperatures from the physiological manikin, it is clear that they do not show the same trend.

6.1.4.1 Correlations

A good correlation with the wear trial would indicate that the physiological manikin can be used to test garments and predict the physiological response. The correlation with the wear trial did not prove to be as a better predictor of physiological response than the hot plate as anticipated before the tests were run. This could be due to potential equipment issues with the physiological manikin discovered after testing was complete. Tests were rerun but it is unclear if all issues were resolved. In the past, the physiological manikin was shown to be a relatively good predictor of physiological response. The correlation, shown in Figure 6.3 was lower than what was seen for the sweating hot plate correlations and the sweating manikin correlations. Possible reason for the physiological manikin not predicting very well are problems with the underlying thermoregulation model, the conditions being used, the presence of the radiant load, and the moisture accumulation in the under layers.

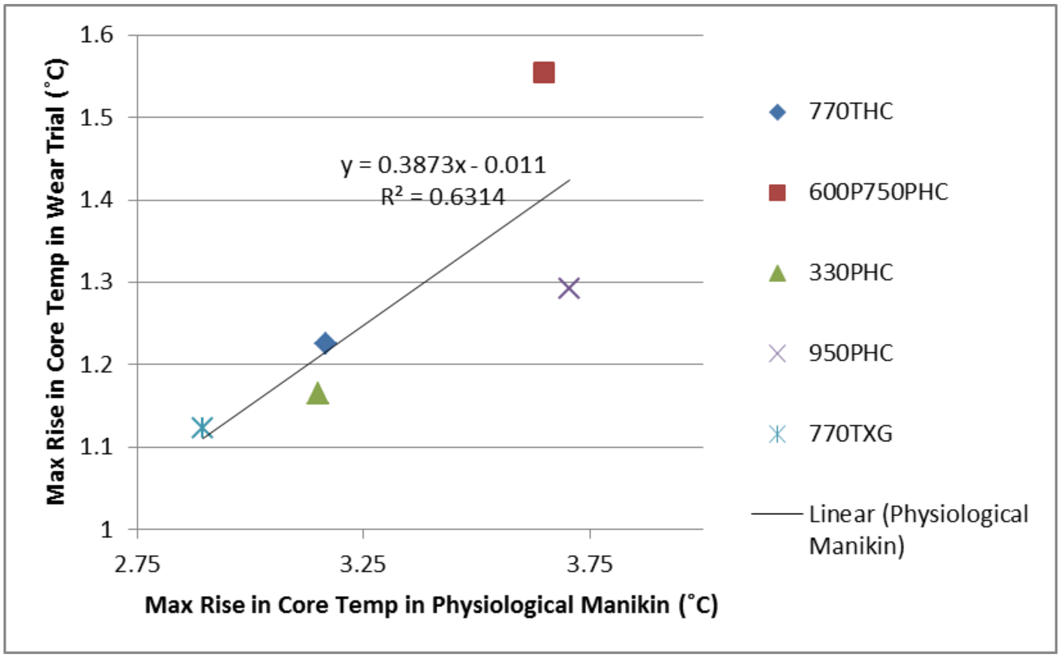


Figure 6.3: Correlation between the Maximum Rise in Core Temperature and the Maximum Rise in Core Temperature Seen on the Physiological Manikin

6.2 Virtual Modeling

6.2.1 Materials

No fabric materials were used for the actual virtual modeling. Rather, values taken from the sweating manikin testing were used in the RadTherm® program.

6.2.2 Virtual Modeling Procedure

The insulation and evaporative resistance values from the sweating manikin were entered into the RadTherm® program for each section of the body. The conditions were set to be the same as what was in the wear trial at 34°C and 30% RH. For the radiant load, radiant panels were put into the model to estimate the heat flux generated by the radiant heat sources during the wear trial. In addition to the environmental parameters, a file containing the boundary conditions with the same protocol, in relation to the change in activity level and the activity type, used in the physiological manikin was imported. The file containing the activity level and activity type boundary conditions can be found in Appendix J. Figure 6.4 shows the model while it is running in RadTherm®. The grey area on the left of the screen shows where all of the parameters are inputted into the program and where the layers of each section of the human model are built. The white area contains the human model which is divided up into the parts of the sweating manikin indicated by the different colors. The two rectangles angled in the white area indicate the radiant lamps. After all of the parameters are inputted into the program, the model stimulates the body temperatures over the course of the protocol.

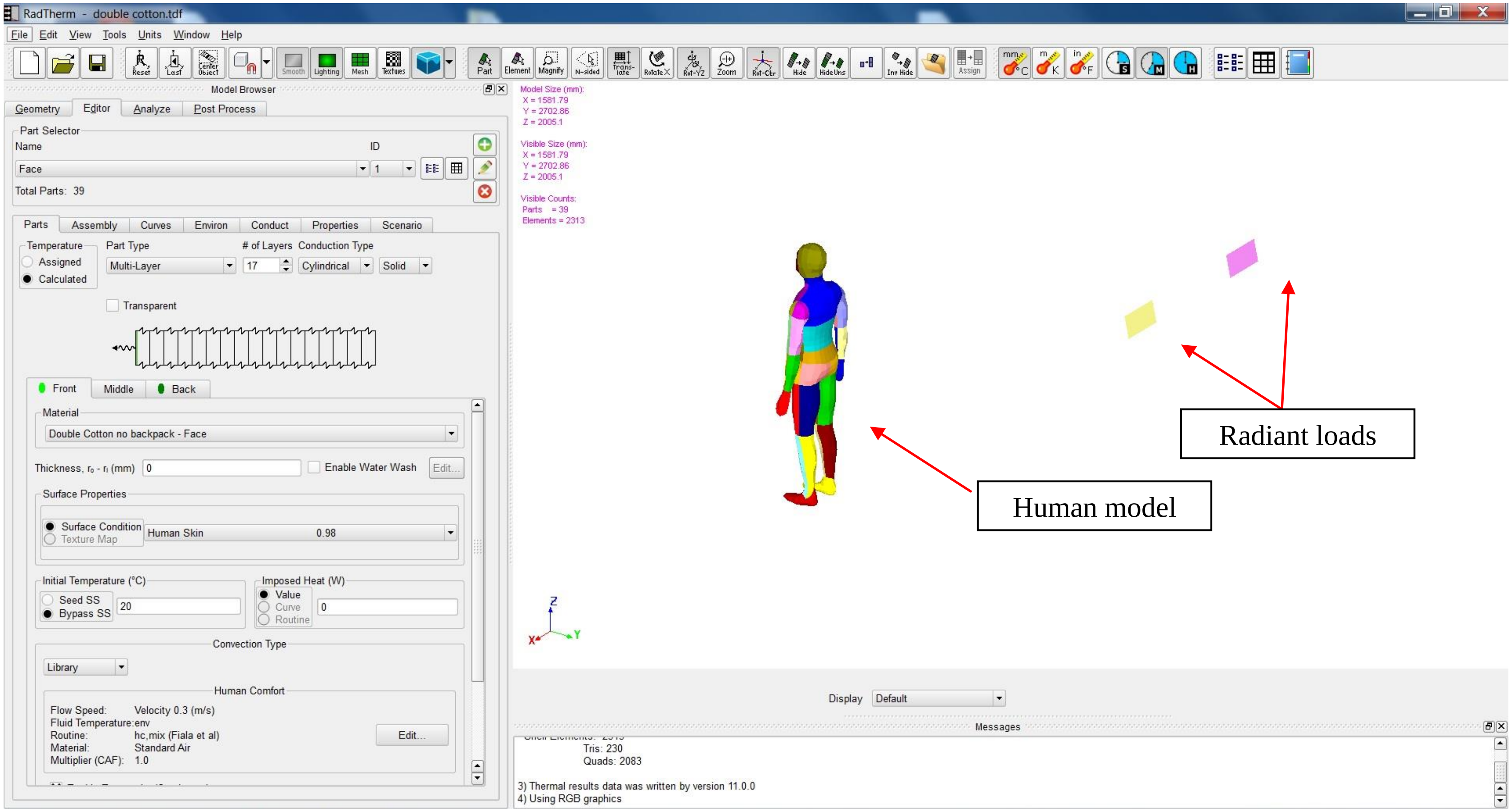


Figure 6.4: RadTherm® Modeling Program

6.2.3 Virtual Modeling Results

The rectal temperature of the physiological manikin over time with each garment, shown compared to the core temperatures in the wear trial in Figure 6.5, was plotted similarly to the wear trial and physiological manikin data.

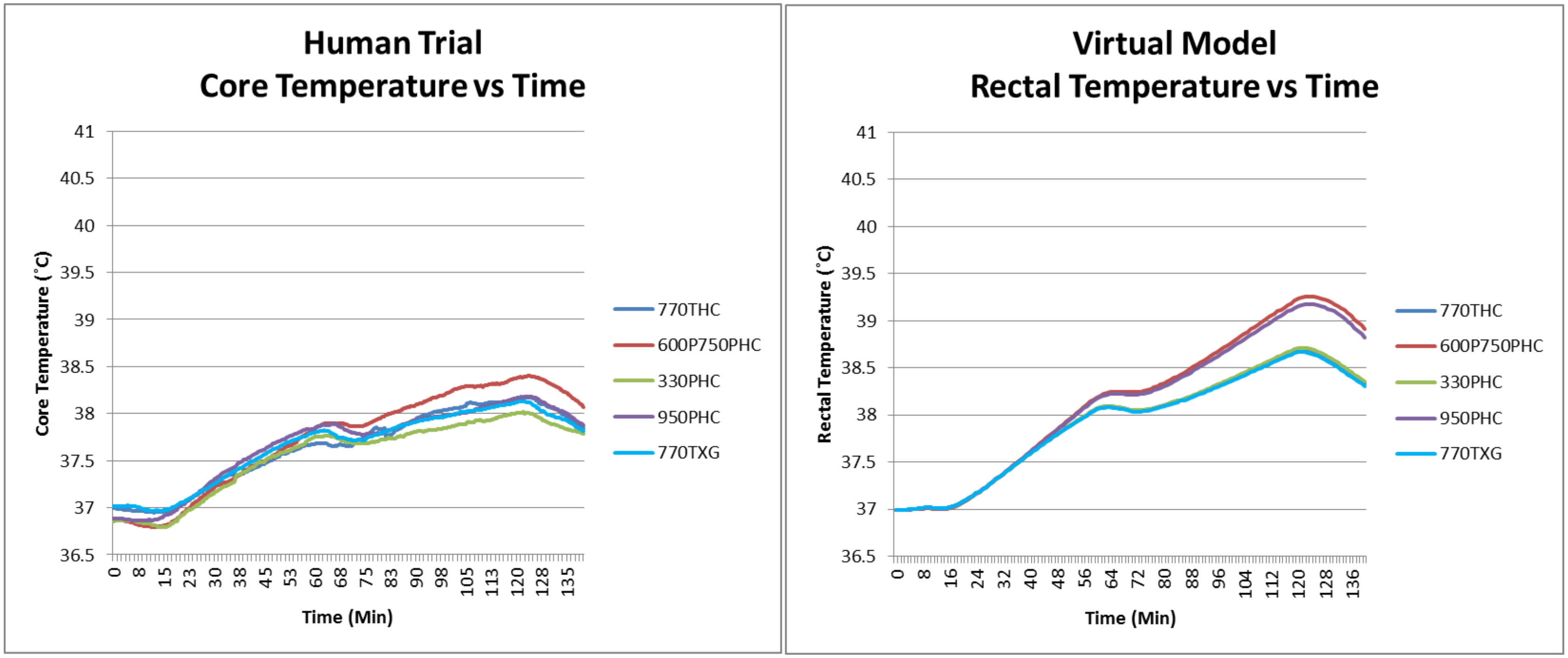


Figure 6.5: Core Temperature over Time from the Wear Trial compared to Rectal Temperature over Time from the Virtual Model

6.2.4 Virtual Modeling Discussion

Since the virtual model used the sweating manikin data and there were no differences seen between the three lighter garments and a minimal difference between the two heavier garments, the same trends were shown in the virtual modeling results. However, since there was a radiant load incorporated into the virtual model, it would not have the same correlation as the sweating manikin compared to the wear trial maximum rise in core temperature. The virtual model over predicted the physiological response similarly to how the physiological manikin did. All of the correlations (Figure 6.6) for the maximum rise in core temperature in the wear trial are summarized in Table 6.3.

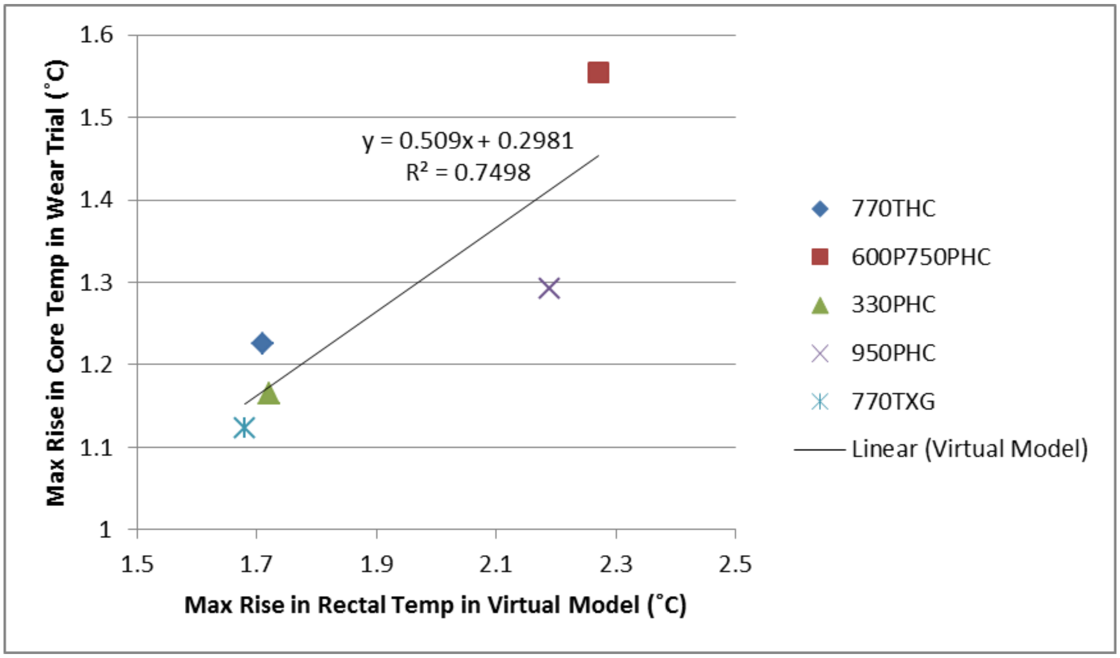


Figure 6.6: Correlation between the Maximum Rise in Core Temperature and the Maximum Rise in Rectal Temperature Seen in the Virtual Model

Table 6.3: Correlation Values for the Maximum Rise in Core Temperature compared to all Instrumentation

Dependent Variable	Independent Variable	R^2 value
Max Core Temp Rise	THL	0.9237
	1/THL	0.9661
	Evap Comp of THL	0.8304
	Weight	0.874
	Thickness	0.8165
	Manikin THL	0.8005
	1/ Manikin THL	0.8214
	Virtual Model Max Core Temp Rise	0.7498
	Physiological Manikin Max Core Temp Rise	0.6314

7 Conclusions and Recommendations

The results from the sweating hot plate shows that all outer shell materials that were tested currently pass the NFPA 1977 THL requirement of 450 W/m^2 and therefore we contend that it is likely set too low. A new recommended value is 565 W/m^2 value, predicted using a combination of the THL and 1/THL estimated using methodology previously used to come up with the THL value in the current NFPA 1971 standard for structural firefighter turnout gear. All of the plain weave fabrics would have passed this new recommendation except for the 9.5 oz/yd^2 plain weave and the double layer fabric system. In addition, all of the twill fabrics would have passed. The new recommended value seems to parallel the results found in the wear trial better than the current THL requirement. Most of the suits would not meet the standard if tested the way they are worn. Testing fabrics with a standard cotton base layer reduced THL by approximately 30%. If fabrics were required to be tested this way, many would not pass the THL requirement including the lightest weight plain weave. In fact, despite the fact that they were lighter weight, the 3.0 and 4.5 oz/yd^2 fabrics did not demonstrate a heat loss advantage over the 6.0 oz/yd^2 fabric. The human response in the lightweight plain weave (3.3 oz/yd^2) was better than predicted by the THL. Even with the radiant load that hindered the light weight plain weave's performance in the wear trial, it still had a lower maximum rise in core temperature. It is unclear why the THL results on the hot plate were lower than expected for the 3.3 oz/yd^2 fabric because no variables, besides weight and thickness, were known to be different. When looking at the manikin and the sweating hot plate THL, no significant difference was seen between a plain weave and twill weave fabric. There was also no significant difference between the 7.1 oz/yd^2 cotton base layer and the 5.2

oz/yd^2 modacrylic/FR rayon blend base layer from the wear trial tested with the outer shell on the sweating hot plate and the sweating manikin.

The manikin THL shows differences between the two heavier garments used in the wear trial (double layer and 9.5 oz/yd^2 plain weave) and the other wear trial garments. With the three garments that had reinforcements on them, there were no significant differences in the THL between the garment having no reinforcements and the garment having the standard amount of reinforcements. However, the garment with the extra reinforcements caused a noticeably lower total heat loss. It is important to note that the garment with the extra reinforcements did not exceed the maximum surface area of reinforcements allowed on the garment by the NFPA standard.

When relating the instrumentation to each other, the plate THL and the manikin THL have good correlations with a similar design but when changing the amount of reinforcements on the garment, the correlation is no longer good. In addition, the sweating manikin, physiological manikin, and the virtual model did not correlate to the wear trial better than the plate THL as expected. This could be because the accessories used on the garment level compressed the differences from garment to garment whereas on the plate the only component being tested is the fabric itself so all differences would be amplified. However, it is important to note that in the wear trial, the heaviest weight double layer garment was significantly more detrimental to the core temperature than the other suits. The sweating manikin, physiological manikin, and the virtual model were all able to show that the double layer system was significantly worse than the other suits and therefore are able to show differences when they are most important. The skin temperature data showed that all of the possible wildland conditions that may be experienced during wildland firefighting must be taken into account when selecting a suit because the radiant load has a large effect on the physiological response. This explained why the lightweight garment was not significantly better than all of the other garments with its physiological response. When examining all of the instrumentation, 1/THL was shown to be the best predictor of the physiological response under the assumption that the plate THL is a direct comparison to the physiological response. It is important to note that since the hot plate is not designed to take into account changes to the garment design, through differing amount of reinforcements, and changes to the overall ensemble such as differing base layers or accessories, it cannot always be considered the best predictor.

7.1 Future Research and Recommendations

A few minor parts of the project could be looked into a little further. First, a weighting system to make a more direct comparison between the plate THL and the physiological response can be looked into but this would only be able to account for the base layers. This would look into finding out how much of the body is covered by just the outer garment and how much of the body is covered by the garment and a base layer. Testing could prove whether a more accurate THL value could be found by combining both the THL of just the outer layer and the THL of the outer layer with the base layers. Also further investigation of the new value of the THL that was found could be done.

An important extensive investigation is exploring how wildland firefighter garments affect the physiological response of wildland firefighters in various scenarios that firefighters have to encounter. This is an important factor to investigate because garments that may perform well in one scenario may not perform as well in a different weather scenario. This was indicated in the physiological wear trial. Further investigations could be conducted in physiological wear trials with low, mid, and high wind levels, as well as no radiant load, medium radiant load, and the highest radiant load that could be exposed to human subjects in a wear trial. However, since some environmental conditions cannot be explored because they are too extreme for a wear trial, a more extensive study could be done in the virtual model. First, it is clear that the virtual model is responding too quickly and the model itself will likely need to be adjusted. Very extreme radiant loads and other conditions that might be seen in wildland firefighting on more rare occasions can be explored. In addition, the lengths of time more typical for a work period that a wildland firefighter might have to encounter can actually be tested. The virtual model also has a capability to load historical weather data. Weather scenarios that have actually occurred during wildland fires can be loaded and run to see how the garments affect the physiological response in these conditions.

In relation to the virtual model, further investigation can also be done with the technique of building the garments used in the model. In the use of the virtual model in this study, the average insulation and resistance values were entered into the system for each body part based on outputs from the sweating manikin. Using the approach of entering sweating manikin values, the values from each of the individual reps before they are averaged can be used and run in three separate reps. Running the model this way would be helpful because the variability in each of the sweating manikin replicates would not be hidden by the average value that is calculated from the three replicates. Also, a virtual garment can be built using hot plate material values and air layers. This can be compared back to the manikin virtual model results as well as to the human test results. Validation of this capability of the model can show how accurate the virtual model can be with its prediction of physiological response. This is important because a researcher might only have access to hot plate data. Also, this application could be used to test how a material not yet purposed into a garment would be predicted to perform. Finally, with this capability individual components of the ensemble can be tweaked to explore what effect it might have on the garment.

The effects of clothing ventilation can also be explored on the physiological manikin. Slits can be put into the existing garments and compared back to the clothing with no ventilation. The slits can be strategically designed and placed to ensure that they meet the requirements of protection and reinforcement but still provide a benefit when movement is involved. Ventilation has been shown to relieve heat stress dramatically in impermeable garments but further investigation would need to be done with permeable garments. In addition to the release of heat, ventilation also breaks up the still air layers within the garments therefore decreasing the insulation that the air layers provide. Because decreasing the thickness of a fabric will both increase the total heat loss and decrease the protective factor, it is important that other forms of garment design are looked into that will improve the factor of heat loss without hindering how much protection it can provide. This is a likely way to achieve this goal.

Finally, since the garments that we were able to use in the wear trial were limited in number and were not all direct comparisons, it is important to look into more direct comparisons. A direct comparison between a twill garment and a plain weave garment of the same weight is important on humans. In addition, having a range of all of the weights with the same fabric and the same weave is necessary to form a correlation with no confounding variables. It is necessary to compare more than four different garments in order to get a correlation with statistical confidence in the relationship between the different instruments. The more values that are available, the more complete the assessment, and possibly more accurate, the correlation will be. Finally, the layering factor can be further investigated in a wear trial. A double layer garment that has the same total weight/thickness as a single layer garment must be compared in order to see how the layers alone affect physiological response. Layering in relation to reinforcements on the garments can also be looked into in a wear trial to see if there is a difference between them. The surface area of the reinforcements on the suit with the extra reinforcements tested on the sweating manikin still did not exceed the maximum surface area that a garment can have before having to be tested with its reinforcements so it is important that a garment that does not meet these requirements also be tested. The nature of the reinforcements would be important to look into as well. Covering a garment with pockets may be acceptable while covering with knee pad or trim may not be.

For the garments tested in the wear trial, it is important to compare to field studies to ensure that the conditions used in the environmental chamber are giving similar results to what would be seen in the actual environment. Researchers will never be able to fully replicate all the conditions seen by a wildland firefighter, but the research conducted in this project and continued research in this area will hopefully help to make for better gear, better decision making, and a safer work environment.

REFERENCES

[1] CAL FIRE Personal Protective Equipment Working Group, "Wildland Fire Fighting Hazard & Risk Assessment Draft Report."

[2] G. M. Budd, J. R. Brotherhood, A. L. Hendrie, S. E. Jeffery, F. A. Beasley, B. P. Costin, W. Zhien, M. M. Baker, B. N. Hoschke, B. V Holcombe, N. P. Cheney, and M. P. Dawson, "Project Aquarius 13 . The thermal burden of high insulation and encapsulation in wildland firefighters clothing," *International Journal of Wildland Fire*, vol. 7, no. 2, pp. 207–218, 1997.

[3] A. Beaver, "Evaluating Risk and Reward Relationships in Wildland Firefighter Safety," Whitehorse, Yukon, 2001.

[4] B. N. Hoschke, "Standards and Specifications for Firefighters' Clothing," *Fire Safety Journal*, vol. 4, pp. 125–137, 1981.

[5] Safety and Health Working Team, "Wildland Firefighter Fatalities in the United States : 1990-2006," 2007.

[6] Conference Papers, "Heat Stress," in *Wildland Firefighter Health and Safety-Recommendations of the April 1999 Conference*, 1999, pp. 32–37.

[7] NIOSH, "Wildland fire fighter dies from hyperthermia and exertional heatstroke while conducting mop-up operations - texas," *Centers for Disease Control and Prevention*. [Online]. Available: http://www.cdc.gov/niosh/fire/reports/face201117.html. [Accessed: 02-Nov-2012].

[8] M. Desmond, *On the Fireline: Living and Dying with Wildland Firefighters*. Chicago: University of Chicago Press, 2007, pp. 1–369.

[9] G. M. Budd, J. R. Brotherhood, A. L. Hendrie, S. E. Jeffery, F. A. Beasley, B. P. Costin, W. Zhien, M. M. Baker, N. P. Cheney, and M. P. Dawson, "Project Aquarius 6. Heat load from exertion, weather, and fire in men suppressing wildland fires," *International Journal of Wildland Fire*, vol. 7, no. 2, pp. 119–131, 1997.

[10] International Association of Firefighters, "Rehab presentation - section 2 (Heat Stress and the Firefighter)." [Online]. Available: http://www.iaff.org/hs/eirp/files/instructor materials/rehab presentation - section 2.ppt.

[11] M. Keifer and R. J. Mangan, "Idaho and Montana – Fire Season 2000 Wildland Firefighter Injuries in Idaho and Montana – Fire Season 2000," Seattle, 2004.

[12] C. B. Wenger, M. N. Sawka, K. B. Pandolf, R. F. Johnson, J. L. Kobrick, S. L. Gaffin, R. W. Hubbard, S. A. Nunneley, and M. J. Reardon, *Medical Aspects of Harsh Environments, Volume 1*, vol. 1. Washington, DC: Office of the Surgeon General at TMM Publications, 2001, pp. 51–86, 135–230.

[13] G. Havenith, "Heat balance when wearing protective clothing.," *The Annals of occupational hygiene*, vol. 43, no. 5, pp. 289–96, Jul. 1999.

[14] R. F. Goldman, "Assessment of Thermal Comfort," *ASHRAE Transactions*, vol. 84, no. 1, pp. 1–6, 1978.

[15] M. Cabanac, "Physiological Signals for Thermal Comfort," in *Bioengineerg, Thermal Physiology and Comfort*, K. Cena and J. A. Clark, Eds. Amsterdam: Elsevier, 1981, pp. 181–192.

[16] F. Varley, "A Study of Heat Stress Exposures and Interventions for Mine Rescue Workers," Spokane, WA, 2004.

[17] P. a Hancock and I. Vasmatzidis, "Effects of heat stress on cognitive performance: the current state of knowledge.," *International journal of hyperthermia : the official journal of European Society for Hyperthermic Oncology, North American Hyperthermia Group*, vol. 19, no. 3, pp. 355–72, 2003.

[18] D. S. Moran, K. B. Pandolf, and F. Derrick, "TECHNICAL REPORT NO . T99-XX A PHYSIOLOGICAL STRAIN INDEX (PSI) TO EVALUATE HEAT STRESS," 1999.

[19] I. Holmér, "Protective clothing and heat stress," *Ergonomics*, vol. 38, no. 1, pp. 166–182, 1995.

[20] I. Holmér, H. Nilsson, G. Havenith, and K. Parsons, "Clothing Convective Heat Exchange-Proposal for Improved Prediction in Standards and Models," *The Annals of occupational hygiene*, vol. 43, no. 5, pp. 329–37, Jul. 1999.

[21] R. F. Goldman, "Thermal Comfort Factors: Concepts and Definitions," in *Clothing Comfort: Interaction of Thermal, Ventilation, Construction, and Assessment Factors*, N. R. S. Hollies and R. F. Goldman, Eds. Ann Arbor, Michigan: Ann Arbor Sceince Publishers, Inc., 1977, pp. 3–8.

[22] E. A. McCullough, M. Kwon, and H. Shim, "A comparison of standard methods for measuring water vapour permeability of fabrics," *Measurement Science and Technology*, vol. 14, no. 8, pp. 1402–1408, Aug. 2003.

[23] R. F. Goldman, “Clothing design for comfort and work performance in extreme thermal environments.,” *Transactions of the New York Academy of Sciences*, vol. 36, no. 6. pp. 531–44, Jun-1974.

[24] R. F. Goldman, “Heat Stress In Firefighting- The Relationship Between Work, Clothing and Environment.pdf,” *Fire Engineering*, vol. May 1990, pp. 47–52, 1990.

[25] National Fire Protection Association, “NFPA 1977: Standard on Protective Clothing and Equipment for Wildland Fire Fighting.” National Fire Protection Association, Quincy, MA, pp. 1–67, 2011.

[26] R. M. Duffy, W. M. Lambert, L. Anderson, U. F. Service, E. Mt, R. A. Freese, G. M. Company, M. Nh, and P. A. Gleason, “Report on Comments — Copyright , NFPA 1977,” 2004.

[27] Anonymous, “Single Layering Cargo Pants,” 2006. [Online]. Available: http://www.wildlandfire.com/hotlist/showthread.php?p=9251. [Accessed: 15-Apr-2012].

[28] M. Walker, “David Moore Interview.” Raleigh, NC, 2012.

[29] K. Crippen and D. Jose, “Physiological Comfort Factors of Clothing Systems,” in *Combined Proceedings of ACPTC Eastern, Central & Western Regional Meetings*, 1975, pp. 177–180.

[30] P. A. Thomas and R. S. McAlpine, *Fire In the Forest*. Cambridge: Cambridge University Press, 2010.

[31] J. a Rodríguez-Marroyo, J. López-Satue, R. Pernía, B. Carballo, J. García-López, C. Foster, and J. G. Villa, “Physiological work demands of Spanish wildland firefighters during wildfire suppression.,” *International archives of occupational and environmental health*, vol. 85, no. 2, pp. 221–8, Feb. 2012.

[32] B. C. Ruby, T. C. Shriver, T. W. Zderic, B. J. Sharkey, C. Burks, and S. Tysk, “Total energy expenditure during arduous wildfire suppression.,” *Medicine and science in sports and exercise*, vol. 34, no. 6, pp. 1048–54, Jun. 2002.

[33] B. Aisbett, a Wolkow, M. Sprajcer, and S. a Ferguson, “‘Awake, smoky, and hot’: Providing an evidence-base for managing the risks associated with occupational stressors encountered by wildland firefighters.,” *Applied ergonomics*, vol. 43, no. 5, pp. 916–25, Sep. 2012.

[34] B. J. Sharkey and S. E. Gaskill, “Fitness and Work Capacity,” 2009.

[35] E. Quinn, "MET- The standard metabolic equivalent," *Sports Medicine*, 2007. [Online]. Available: http://sportsmedicine.about.com/od/glossary/g/MET.htm. [Accessed: 08-Feb-2013].

[36] P. N. Omi, *Forest Fires*. Santa Barbara, CA: ABC-CLIO, Inc., 2005, pp. 229–230.

[37] V. Miller, "A Multi-Layered Issue: Double-layer PPE doesn't protect against heat injury," *Fire Rescue Magazine*, Jul-2008.

[38] "Outfitting Wildland Firefighters," *Nova Online*, 2002. [Online]. Available: http://www.pbs.org/wgbh/nova/fire/figh_nf.html. [Accessed: 10-May-2012].

[39] "Protective Clothing:Wildland Gear," *Santa Clara County Fire Department*. [Online]. Available: http://www.sccfd.org/clothing_wildland.html.

[40] D. J. Gohlke, "History of the Development of the Total Heat Loss Test Method," in *Performance of Protective Clothing*, Sixth Volu., 1997, pp. 191–206.

[41] "ASTM F 1868 - 09 Standard Test Meethod for Thermal and Evaporative Resistance of Clothing Materials Using a Sweating Hot Plate." 2002.

[42] E. A. McCullough, J. Huang, and C. S. Kim, "An Explanation and Comparison of Sweating Hot Plate Standards." .

[43] *Operation & Maintenance Manual: Holometrix Model TCB-TX - Guarded Hot Plate Thermal Conductivity Measuring System*. Cambridge, MA: Holometrix, Inc., 1982.

[44] K. Ross, "Evaluation of an Instrumented Sweating Manikin for Predicting Heat Stress in Firefighters ' Turnout Ensembles .," North Carolina State University, 2005.

[45] "Newton-34 SN330 Operator ' s Manual." 2007.

[46] "ASTM F1291-10: Standard Test Method for Measuring the Thermal Insulation of Clothing Using a Heated Manikin," pp. 16–20, 2010.

[47] "ASTM F2370-10: Standard Test Method for Measuring the Evaporative Resistance of Clothing Using a Sweating Manikin," pp. 17–22, 2010.

[48] K. Ross, R. L. Barker, and A. S. Deaton, "Translation between Heat Loss Measured Using Guarded Sweating Hot Plate, Sweating Manikin, and Physiologically Assessed Heat Stress of Firefighter Turnout Ensembles," *Performance of Protective Clothing and Equipment: Emerging Issues and Technologies*, vol. STP 1544, pp. 27–47, 2011.

[49] Textile Protection and Comfort Center, “Comfort Performance,” *NC State College of Textiles*, 2012. [Online]. Available: http://www.tx.ncsu.edu/tpacc/comfort-performance/. [Accessed: 15-Feb-2013].

[50] J. W. Domitrovich, “Wildland Firefighter Health and Safety,” University of Montana, 2011.

[51] T. A. Bellingar, “The Development of Prototype Wildland Firefighter Protective Clothing,” Auburn University, 1994.

[52] C. Whitlock and B. J. Sharkey, “Work Capacity Test,” Boise, ID, 2003.

[53] K. Blood and R. Burke, “FURTHER VALIDATION OF THE MODEL-CONTROLLED NEWTON THERMAL MANIKIN AGAINST HISTORICAL HUMAN STUDIES.” pp. 1–5, 2009.

[54] R. Burke, K. Blood, A. S. Deaton, and A. West, “APPLICATION OF MODEL-CONTROLLED MANIKIN TO PREDICT HUMAN PHYSIOLOGICAL RESPONSE IN FIREFIGHTER TURNOUT,” no. 1. pp. 1–5.

[55] M. Hepokoski and T. Schwenn, “RadTherm Presentation.” 2012.

[56] D. Fiala, K. J. Lomas, and M. Stohrer, “A computer model of human thermoregulation for a wide range of environmental conditions: the passive system,” *Journal of applied physiology*, vol. 87, pp. 1957–1972, 1999.

[57] D. Fiala, K. J. Lomas, and M. Stohrer, “Computer prediction of human thermoregulatory and temperature responses to a wide range of environmental conditions,” *International Journal of Biometeorol*, vol. 45, pp. 143–159, 2001.

[58] M. Hepokoski and T. Schwenn, “RadTherm(R) Thermal Analysis Software.” Thermoanalytics, Inc., Calumet Township, MI, pp. 9–19, 2012.

[59] “Nomex(R) IIIA,” *DuPont (TM)*, 2013. [Online]. Available: http://www.dupont.com/products-and-services/personal-protective-equipment/thermal-protective/brands/nomex/products/nomex-iii-a.html. [Accessed: 08-Jul-2013].

[60] Measurement Technology Northwest, “Sweating Guarded Hotplate,” *Measurement Technology Northwest*, 2012. [Online]. Available: http://thermal.mtnw-usa.com/sites/thermal.mtnw-usa.com/files/product_brochures/SGHP Hotplate Spec Sheet.REV01.pdf. [Accessed: 04-May-2012].

[61] Thermal Product Solutions, "Lunaire Steady State/ Stability Test Chamber Operation and Maintenance Manual." Thermal Product Solutions, New Columbia, PA, pp. 1–9, 2006.

[62] E. A. Mccullough and B. W. Jones, "A Comprehensive Data Base for Estimating Clothing Insulation," *ASHRAE*, vol. 2888, pp. 29–47.

[63] Fire Dex, "Chieftain Turnout Gear," *Chief Supply*, 2012. [Online]. Available: http://www.chiefsupply.com/resources/PPG-2012-Spring-PDFs/106-109_Fire-Dex.pdf. [Accessed: 23-May-2013].

[64] R. F. Goldman, "DTIC ADA051276: Prediction of Human Heat Tolerance," Natick, MA, 1977.

[65] J. O. Stull and R. M. Duffy, "Field Evaluation of Protective Clothing Effects on Fire Fighter Physiology_Predictive Capability of Total Heat Loss Test.pdf," *Perfomance of Protective Clothing: Issues and Priorities for the 21st Century*, vol. 7, pp. 481–503, 2000.

[66] R. M. Duffy, W. M. Lambert, G. P. Jirka, P. A. Gleason, M. Ziskin, F. S. Corporation, C. T. Rt, L. Anderson, U. F. Service, E. Mt, R. L. Barker, N. Carolina, N. C. Se, and D. R. Forrest, "Report on Proposals F2005 NFPA 1971 — Copyright, NFPA," Quincy, MA, 2005.

[67] NFPA Committee, "Report on Comments A2006 NFPA 1971 — Copyright, NFPA," Quincy, MA, 2006.

APPENDICES

Appendix A: Total Surface Area of All Reinforcements from NFPA 1977

7.1.6.1* Where the total surface area of all reinforcements exceeds the values in Table 7.1.6.1, the reinforcement composites shall be tested for evaporative heat transfer as specified in Section 8.5, Total Heat Loss Test, and shall have a total heat loss of not less than 450 W/m^2.

Table 7.1.6.1 Total Surface Area of All Reinforcements

Type of Garment	Garment Size	Surface Area ($in.^2$)
Protective upper torso garment	XS	625
	S	687
	M	752
	L	820
	XL	893
	2XL	966
Men's lower torso protective garment	26	534
	28	556
	30	577
	32	599
	34	621
	36	643
	38	665
	40	688
Women's lower torso protective garment	23	534
	25	556
	27	577
	29	599
	31	621
	33	643
	35	665
	37	688
Protective one-piece garment	XS	1070
	S	1166
	M	1264
	L	1365
	XL	1470
	2XL	1580

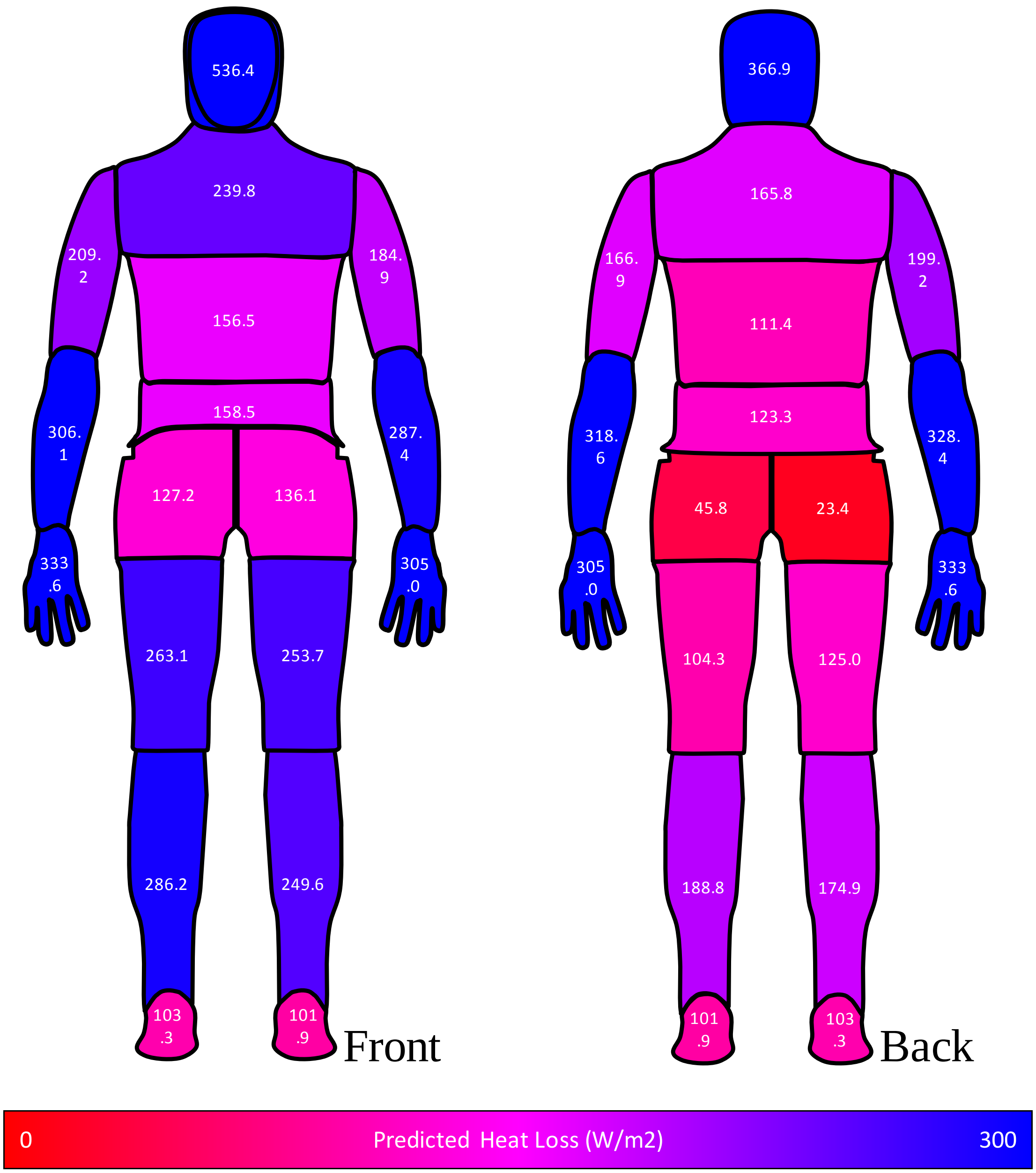
Note: To convert measurements to mm^2, multiply by 645.16.

Appendix B: Guarded Sweating Hot Plate Results

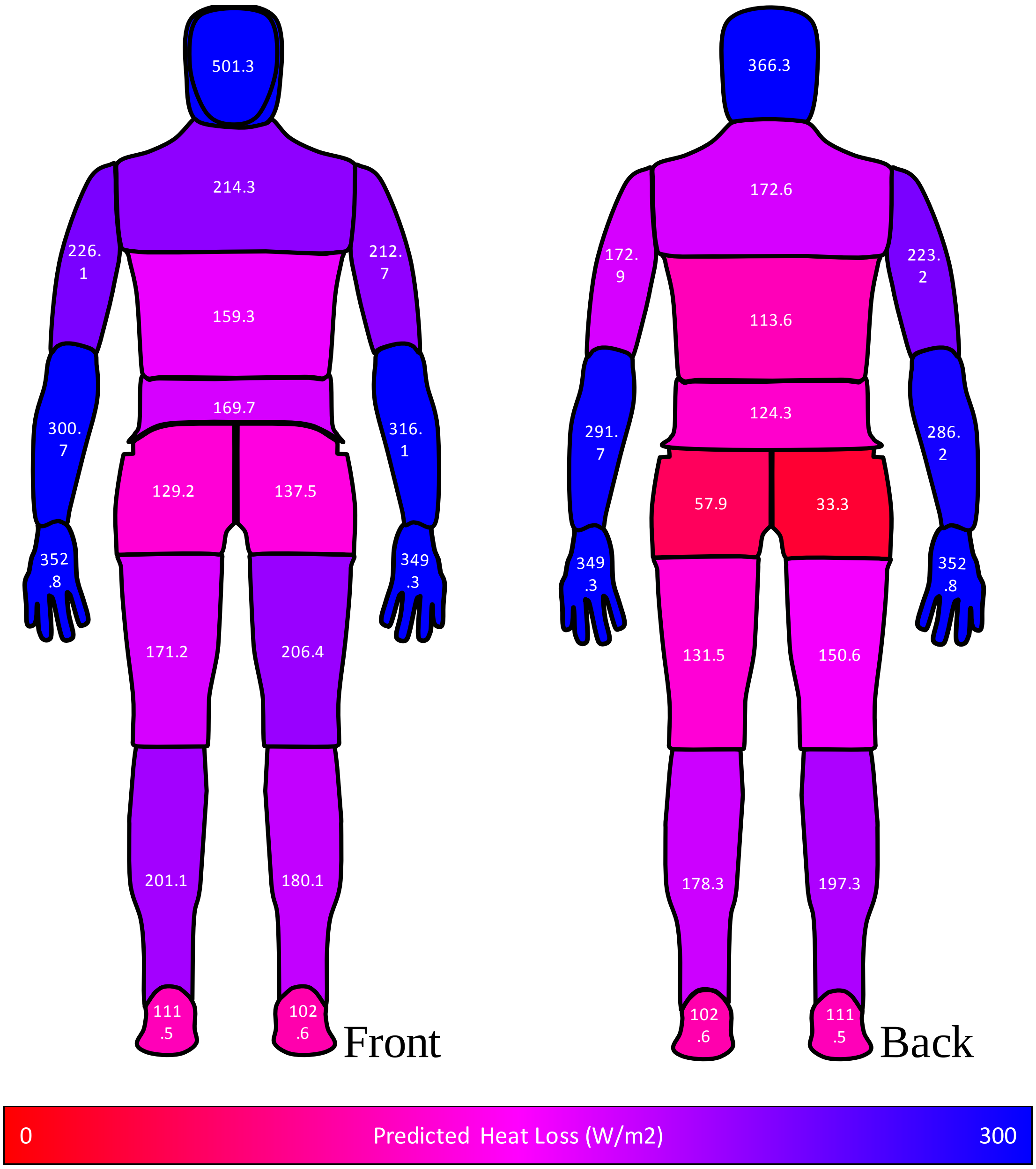
Sample	Q (W/m^2)	C (W/m^2)	E (W/m^2)	R_c ($K*m^2/W$)	R_e ($kPa*m^2/W$)
330P	682.76	147.19	535.57	0.028	0.00317
450P	681.41	150.75	530.66	0.026	0.00323
600P	719.47	155.45	564.02	0.024	0.00283
750P	672.87	151.54	521.33	0.026	0.00335
950P	551.16	147.08	404.08	0.028	0.00534
550T	687.43	152.29	535.14	0.026	0.00317
600T	681.12	149.25	531.87	0.027	0.00321
680T	665.34	152.38	512.95	0.026	0.00347
770T	640.07	133.50	506.57	0.035	0.00400
HC	679.12	153.87	525.25	0.025	0.00330
LC	705.44	147.79	557.65	0.028	0.00290
PE	840.21	181.86	658.36	0.015	0.00192
XG	653.38	130.57	522.81	0.037	0.00333
330PHC	453.06	114.63	338.42	0.047	0.00706
450PHC	481.58	109.99	371.58	0.051	0.00611
600PHC	473.95	116.82	357.14	0.046	0.00651
750PHC	432.24	112.03	320.22	0.049	0.00765
950PHC	420.28	113.77	306.51	0.048	0.00817
770THC	433.94	114.59	319.35	0.047	0.00769
770TLC	492.72	116.28	376.44	0.046	0.00600
770TPE	508.48	128.40	380.07	0.038	0.00600
770TXG	433.86	105.28	328.58	0.055	0.00700
600PLC	502.40	116.45	385.95	0.046	0.00600
600PPE	550.70	128.79	421.91	0.038	0.00500
600PXG	449.32	104.90	344.43	0.055	0.00700
330P330P	467.07	99.69	367.38	0.060	0.00600
550T550T	478.67	103.14	375.53	0.057	0.00600
600P750P	456.76	105.35	351.41	0.055	0.00700
330P330PHC	377.89	85.87	292.03	0.077	0.00900
600P750PHC	335.67	99.35	236.32	0.061	0.01162

Appendix C: Sweating Manikin Heat Loss Diagrams

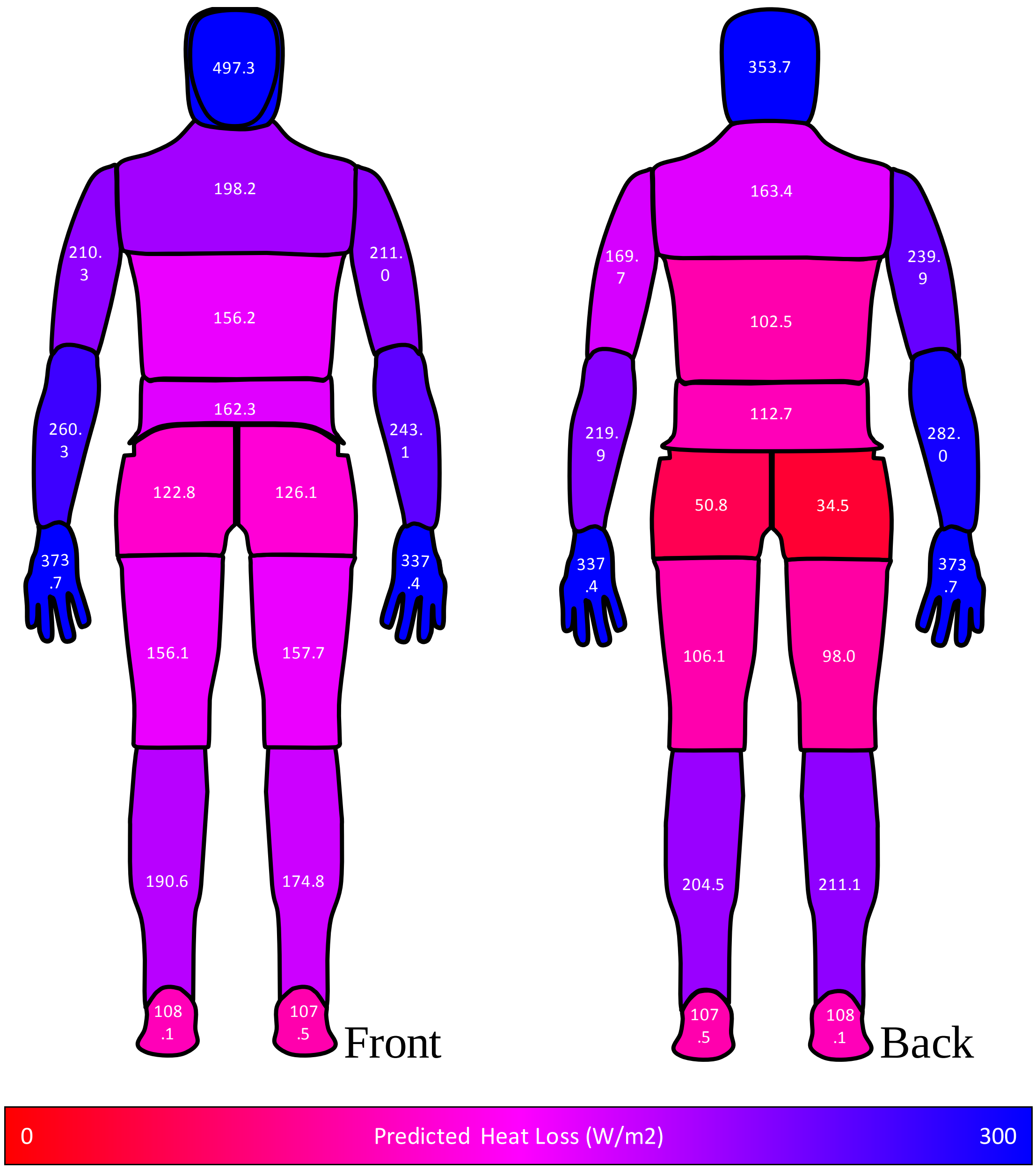
330PHC



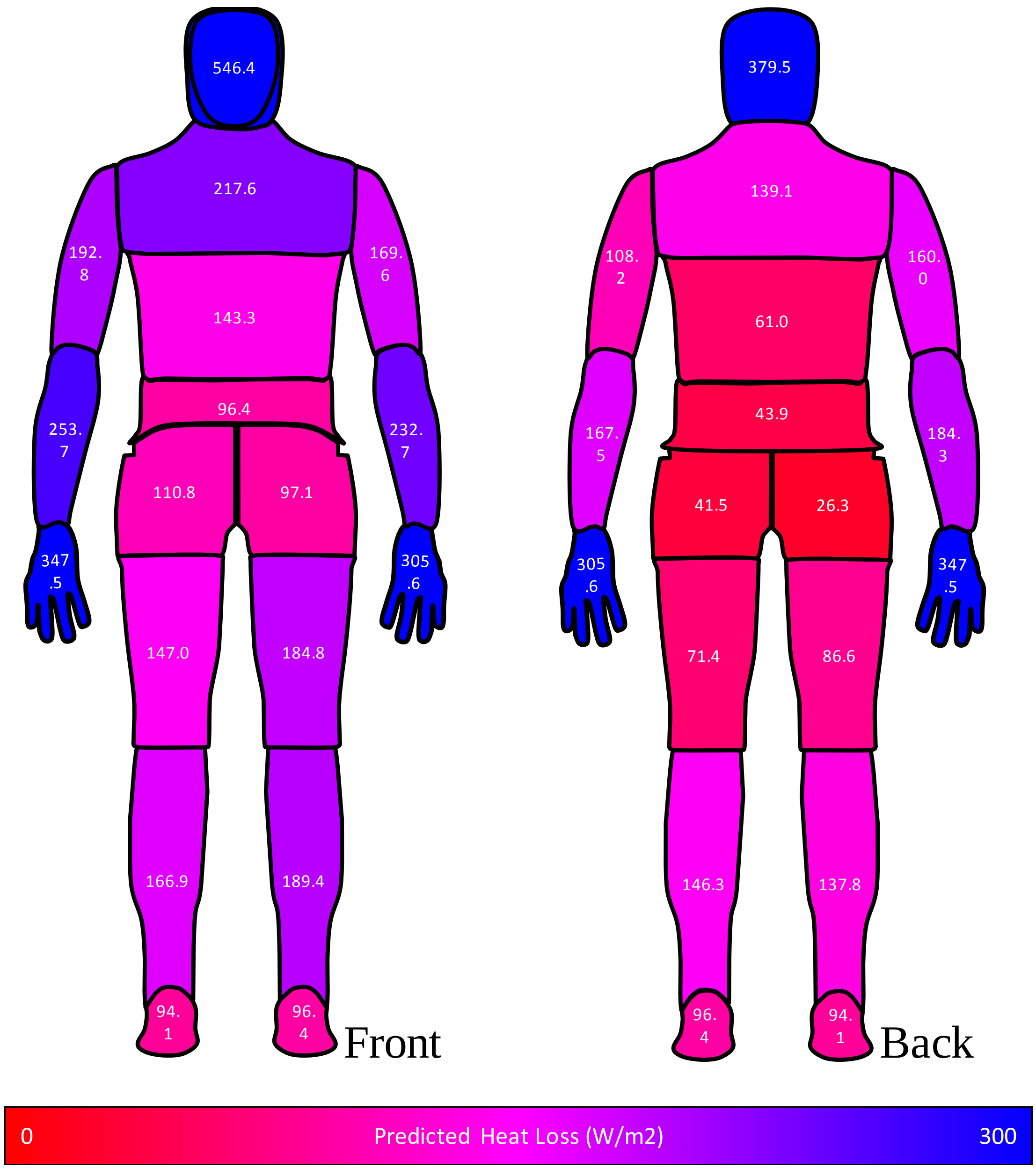
750PHC


501.3
214.3
226.
1
212.
7
159.3
169.7
300.
7
316.
1
129.2
137.5
352
.8
349
.3
171.2
206.4
201.1
180.1
111
.5
102
.6
Front
366.3
172.6
172.
9
223.
2
113.6
124.3
291.
7
286.
2
57.9
33.3
349
.3
352
.8
131.5
150.6
178.3
197.3
102
.6
111
.5
Back
0
Predicted Heat Loss (W/m2)
300

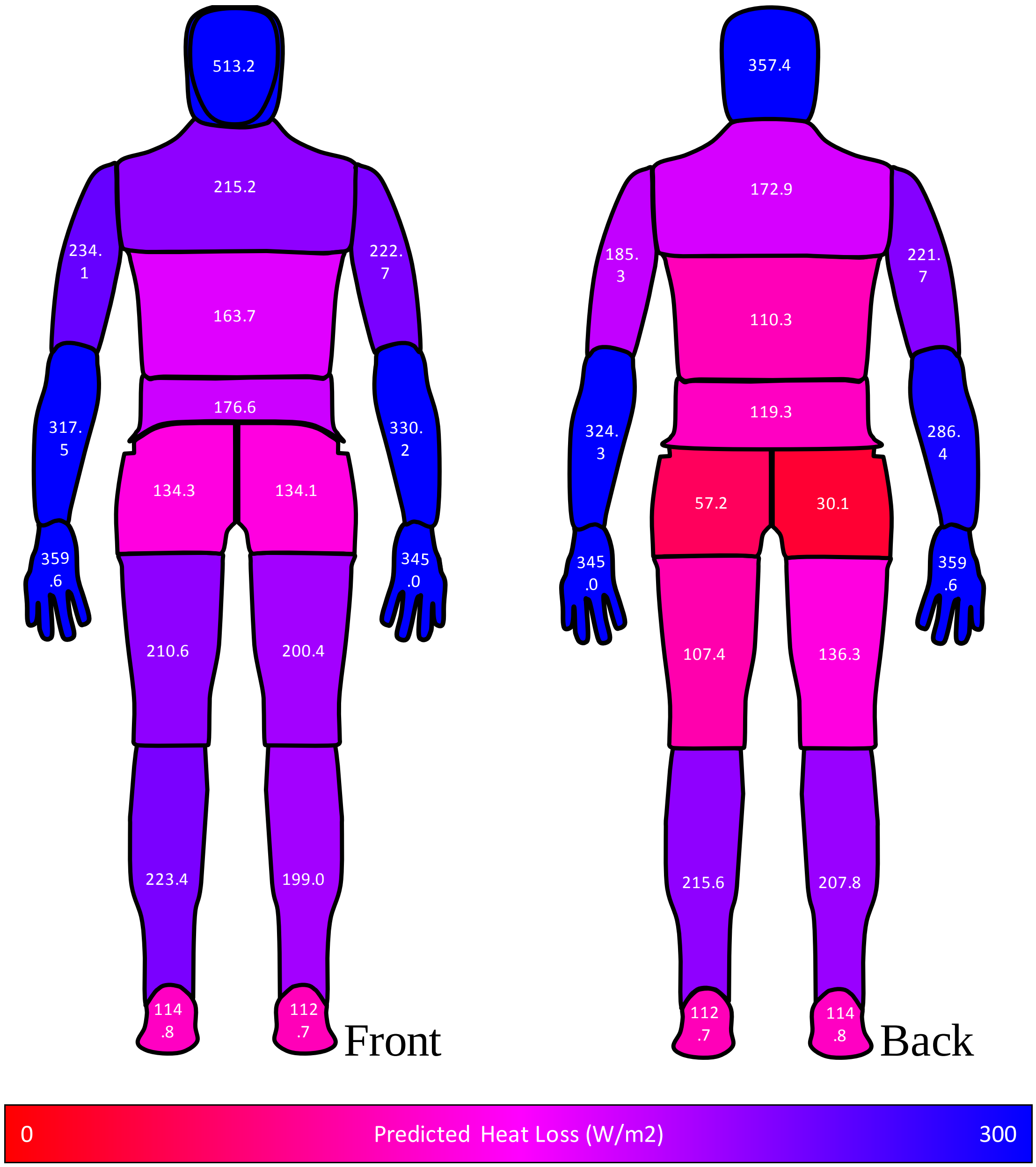
750PHC with extra reinforcements



750PHC no reinforcements

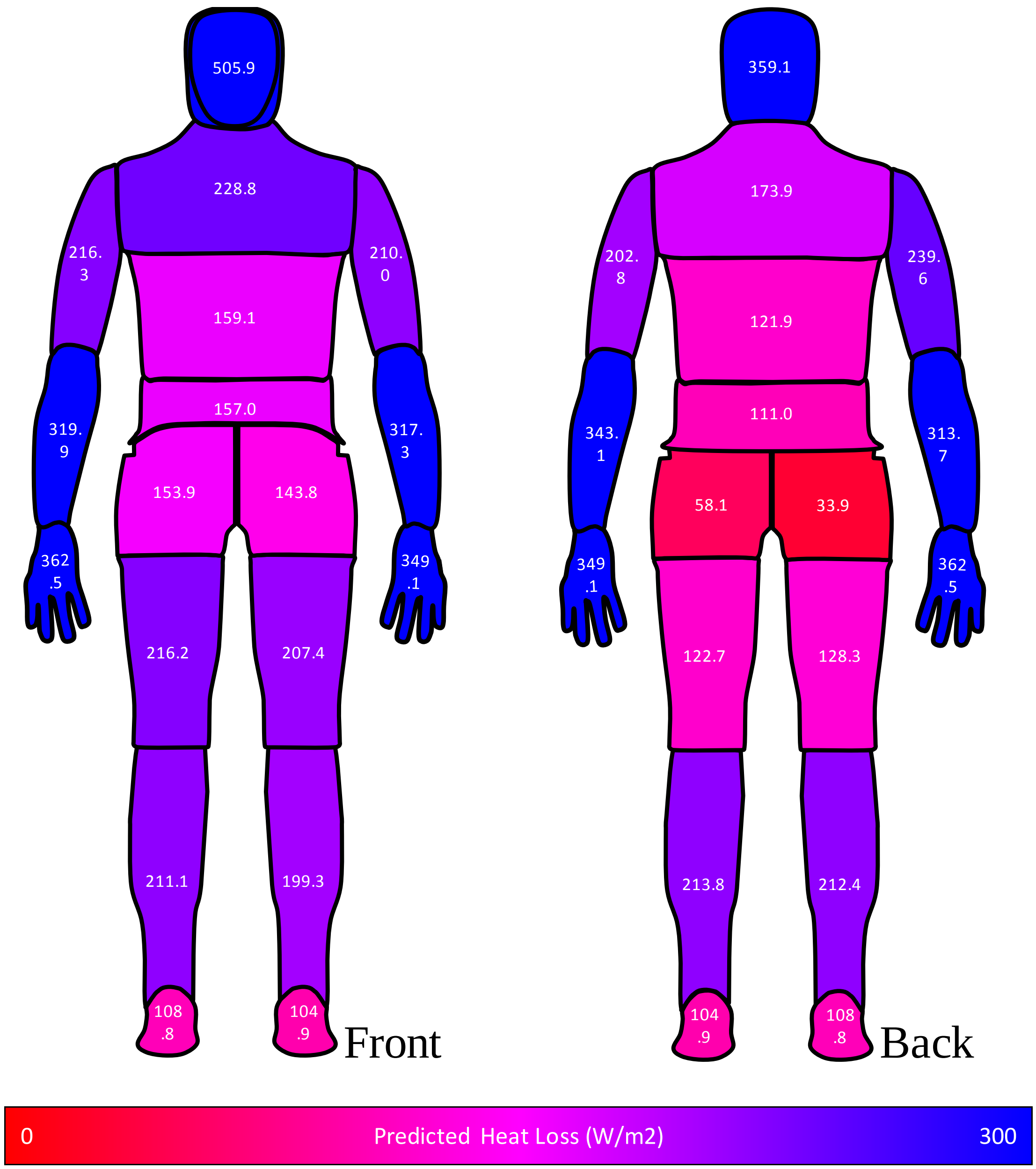


770THC

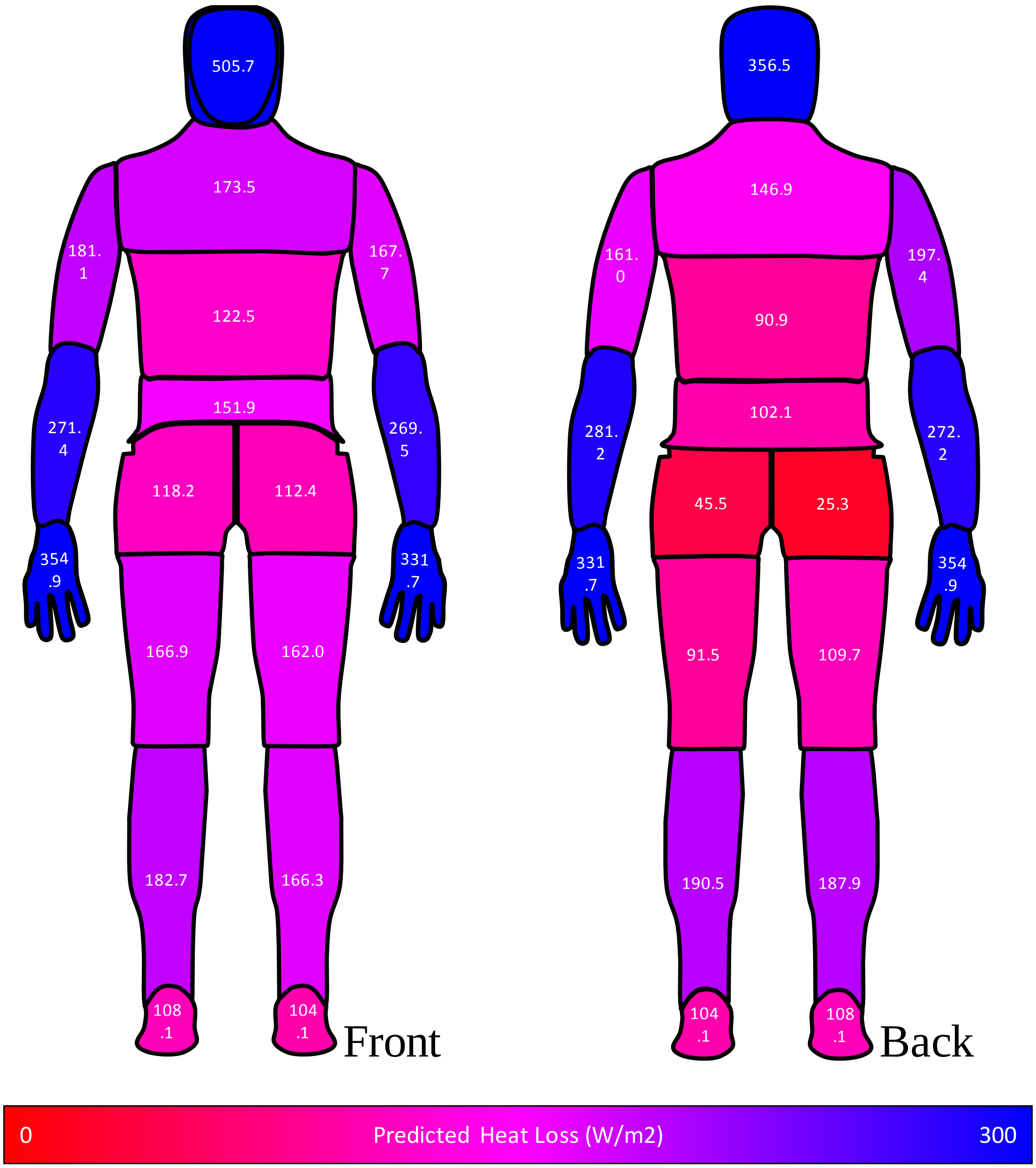


513.2
215.2
234.
1
222.
7
163.7
176.6
317.
5
330.
2
134.3
134.1
359
.6
345
.0
210.6
200.4
223.4
199.0
114
.8
112
.7
Front
357.4
172.9
185.
3
221.
7
110.3
119.3
324.
3
286.
4
57.2
30.1
345
.0
359
.6
107.4
136.3
215.6
207.8
112
.7
114
.8
Back
0
Predicted Heat Loss (W/m2)
300

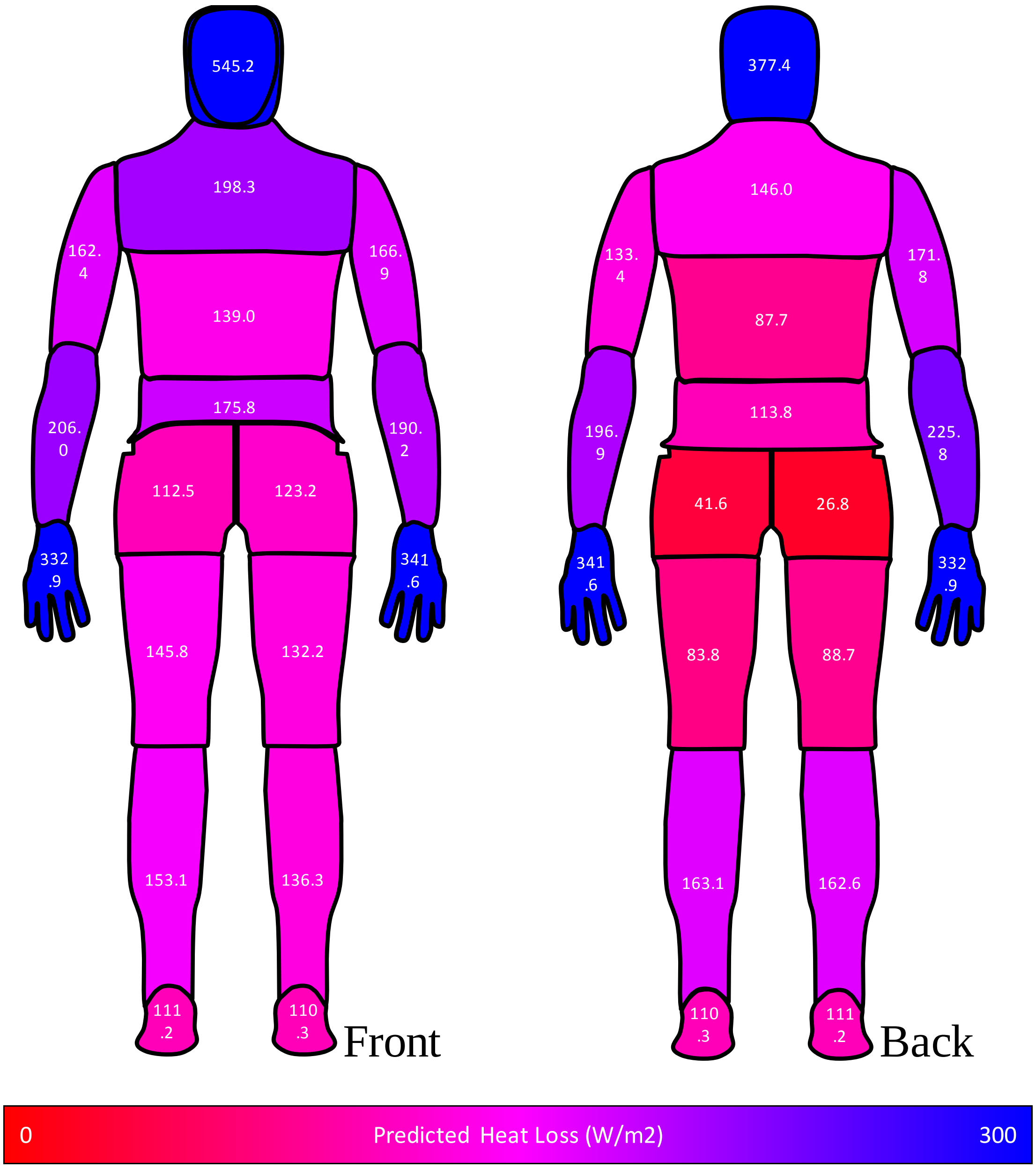
770TXG


505.9
228.8
216.
3
210.
0
159.1
157.0
319.
9
317.
3
153.9
143.8
362
.5
349
.1
216.2
207.4
211.1
199.3
108
.8
104
.9
Front
359.1
173.9
202.
8
239.
6
121.9
111.0
343.
1
313.
7
58.1
33.9
349
.1
362
.5
122.7
128.3
213.8
212.4
104
.9
108
.8
Back
0
Predicted Heat Loss (W/m2)
300

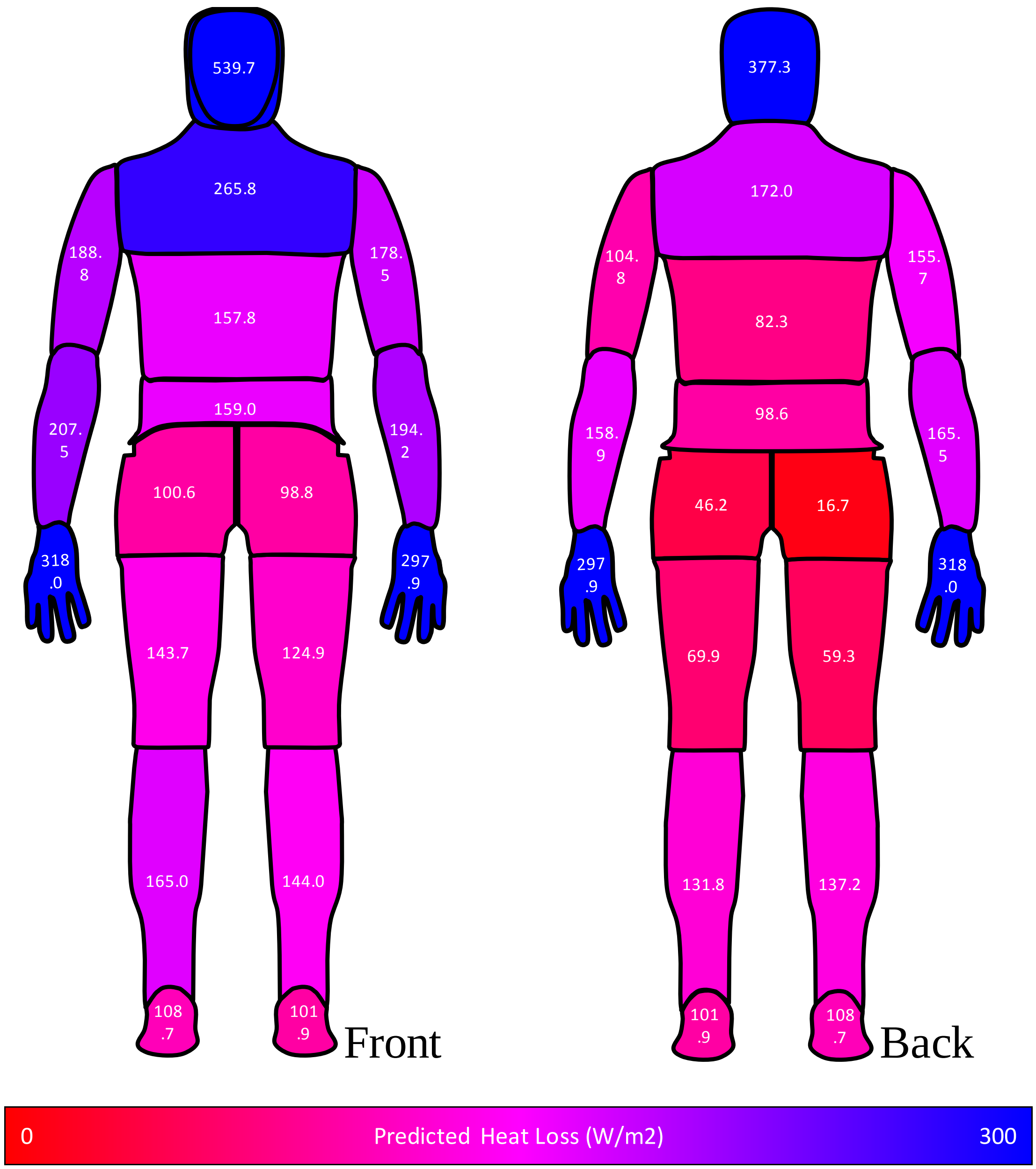
950PHC


505.7
173.5
181.
1
167.
7
122.5
151.9
271.
4
269.
5
118.2
112.4
354
.9
331
.7
166.9
162.0
182.7
166.3
108
.1
104
.1
Front
356.5
146.9
161.
0
197.
4
90.9
102.1
281.
2
272.
2
45.5
25.3
331
.7
354
.9
91.5
109.7
190.5
187.9
104
.1
108
.1
Back
0
Predicted Heat Loss (W/m2)
300

600P750PHC

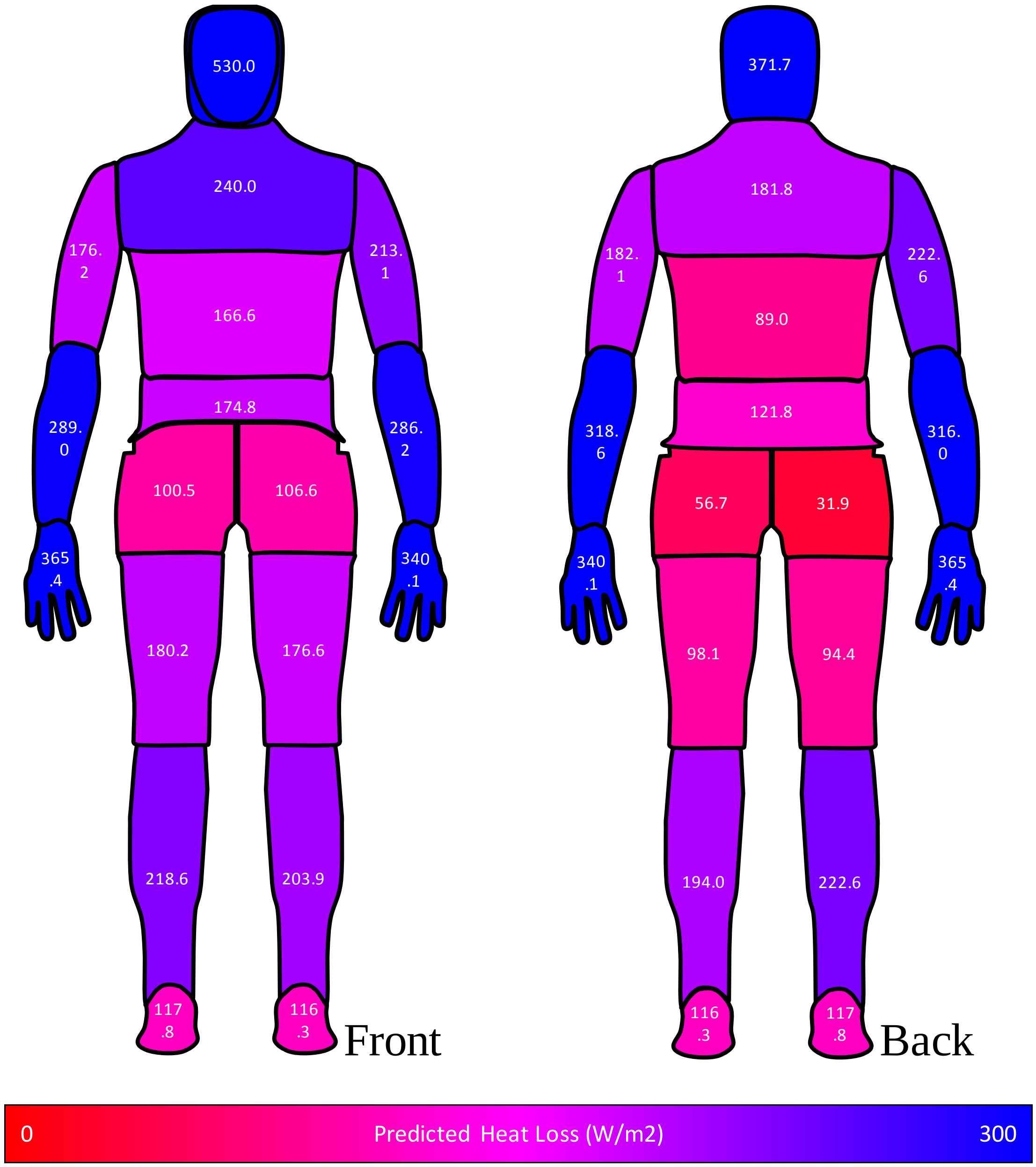

545.2
198.3
162.
4
166.
9
139.0
175.8
206.
0
190.
2
112.5
123.2
332
.9
341
.6
145.8
132.2
153.1
136.3
111
.2
110
.3
Front
377.4
146.0
133.
4
171.
8
87.7
113.8
196.
9
225.
8
41.6
26.8
341
.6
332
.9
83.8
88.7
163.1
162.6
110
.3
111
.2
Back
0
Predicted Heat Loss (W/m2)
300

Cal Fire

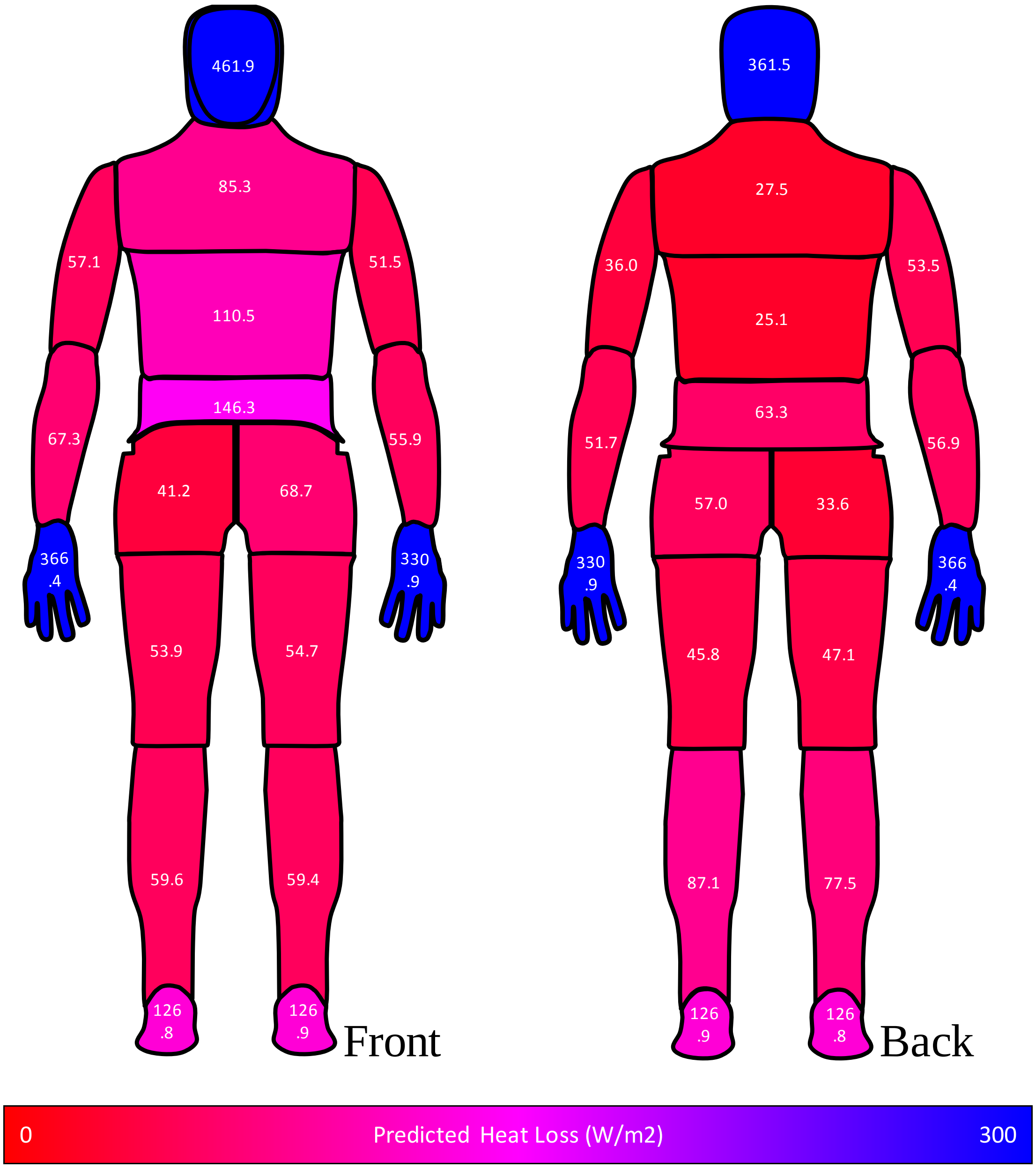


539.7
265.8
188.
8
178.
5
157.8
207.
5
159.0
194.
2
100.6
98.8
318
.0
297
.9
143.7
124.9
165.0
144.0
108
.7
101
.9
Front
377.3
172.0
104.
8
155.
7
82.3
158.
9
98.6
165.
5
46.2
16.7
297
.9
318
.0
69.9
59.3
131.8
137.2
101
.9
108
.7
Back
0
Predicted Heat Loss (W/m2)
300

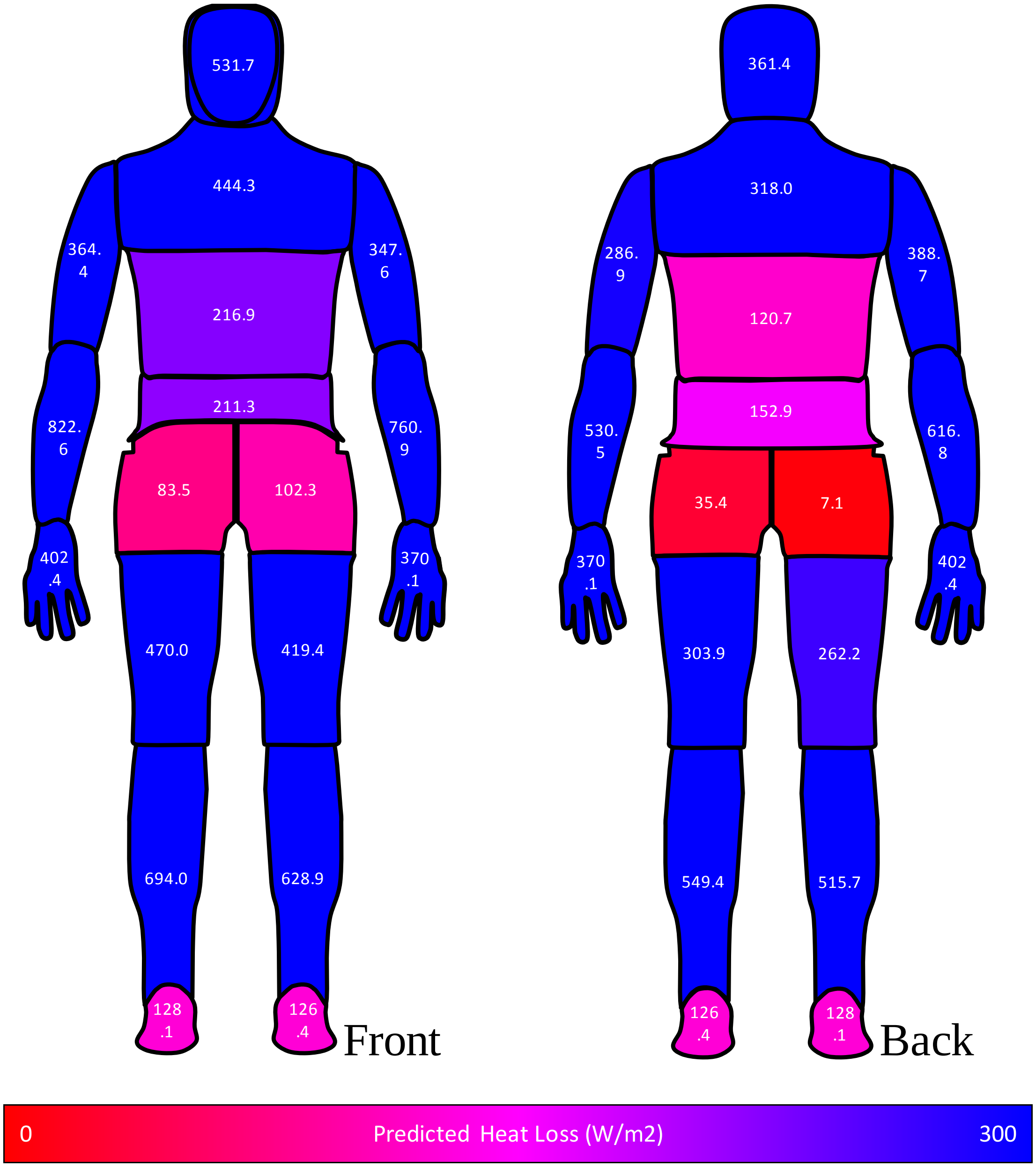
USFS


530.0
240.0
176.
2
213.
1
166.6
174.8
289.
0
286.
2
100.5
106.6
365
.4
340
.1
180.2
176.6
218.6
203.9
117
.8
116
.3
Front
371.7
181.8
182.
1
222.
6
89.0
121.8
318.
6
316.
0
56.7
31.9
340
.1
365
.4
98.1
94.4
194.0
222.6
116
.3
117
.8
Back
0
Predicted Heat Loss (W/m2)
300

Standard Structural Turnout

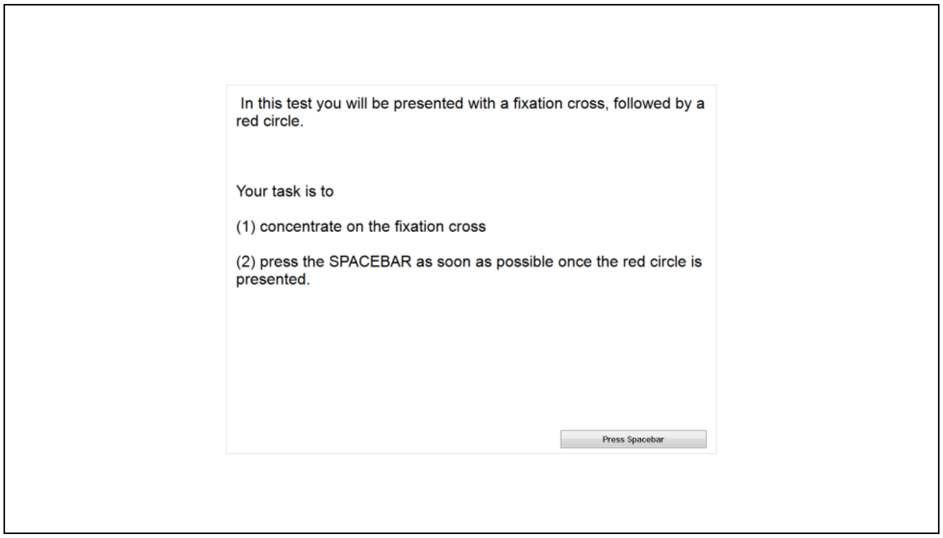


Shorts and T-shirt

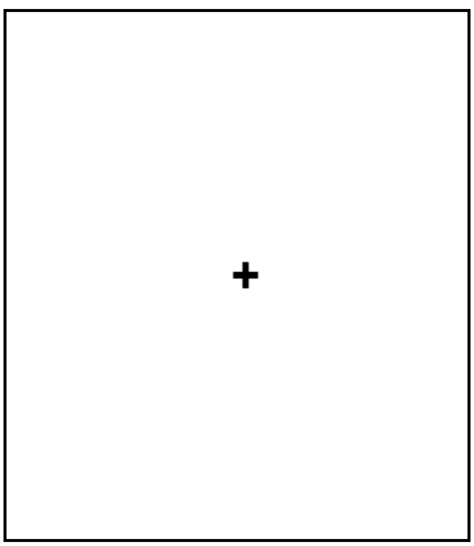


Appendix D: Reaction Time Software Screen

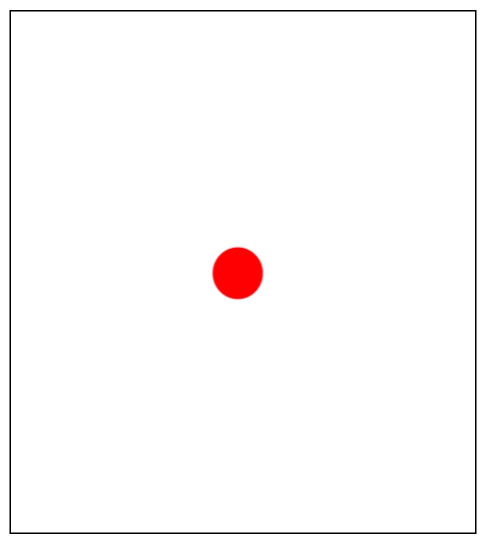
Screen 1: (instructions page)



Screen 2: (fixation cross)



Screen 3: (indication to press space bar)



Appendix E: Physiological Wear Trial Protocol Checklist

INDIVIDUAL WILDLANDS PHYSIOLOGICAL WEAR TRIAL CHECKLIST		
Date:	Subject Number:	Garment ID:

DAY/NIGHT BEFORE		
☐	1) Activate and give subject core temperature pill.	Technician:
☐	2) Have garment set aside for subject.	Pants: ___ ☐ Jacket: ____ ☐ Gloves: ___ ☐ T-shirt: _____ ☐ Briefs: _____ ☐ HR Monitor Strap:____ ☐ Socks ☐ Belt ☐ Helmet ☐ 4 Dermal Patches ☐

MORNING OF		
☐	1) Set up chamber and software	VitalSense ☐ Temp. and Humidity ☐ Treadmill speed: 3mph ☐ Treadmill grade: ☐ Radiant Lights ☐ Netflix and Inquisit ☐

☐	2) Examination form and equipment for the nurse.	Examination Form ☐ Blood pressure cuff ☐ Thermometer ☐
☐	3) Lay out test equipment	Walkie Talkies ☐ Timers ☐ Backup Tablets ☐
☐	4) Activate Dermal Patches	
☐	5) Weigh equipment:	

Overall Weights (kg dry) :

Weight of gear (no HR strap):	

Individual Weights (kg dry):

Underwear:	
T-shirt:	
Jacket:	
Pants:	
Socks:	
Gloves:	
Shoes:	
Belt:	
Helmet:	
HR monitor strap:	

UPON ARRIVAL OF SUBJECT	
☐	1) Verify core temperature capsule is working.
☐	2) Have nurse give examination.

☐	3) Give run through of procedures to subject.	Explain test procedure ☐ Show chamber stretches ☐ Allow subject to choose movie ☐
☐	4) Have subject put on underwear.	
☐	5) Apply dermal patches and heart rate monitoring strap (with heart rate monitor).	
☐	6) Weigh subject and take thermal image: Weight of subject with briefs and instrumentation:	
☐	7) Allow subject to put on rest of clothes	T-shirt ☐ Socks ☐ Pants ☐ Jacket ☐ Helmet ☐ Gloves ☐ Athletic Shoes ☐
☐	8) Weigh subject and take thermal image again: Weight of subject with everything on:	
☐	9) Start timers.	

RESEARCH TEST PROTOCOL:		
☐	1) During 10 minute waiting period (without gloves) have subject fill out:	Subjective test ☐ Reaction time test ☐
☐	2) At 10 min enter chamber and begin walk on treadmill at 3mph and _____% incline.	
☐	3) At 60 min perform stretching exercises.	
☐	5) At 61 min while standing remove gloves and complete: (give water as needed)	Subjective test ☐ Reaction time test ☐

☐	6) Weigh water bottle: Weight of water bottle before opening (g): ___ Weight of water bottle after break(g): ___
☐	7) At 70 min walk on treadmill at 3mph and _____% incline.
☐	8) At 120 min perform stretching exercises.

☐	9) At 121 min while standing remove gloves and complete:	Subjective test ☐ Reaction time test ☐
☐	10) At 130 min exit the chamber and sit in conditioned area and fill out:	Subjective test ☐ Reaction time test ☐
☐	11) At 140 minutes end the test.	

AFTER TEST:	
☐	1) Weigh subject and take thermal images:

Weight of subject with everything on (post wear test):	

☐	2) Have subject fully undress except for underwear, dermal patches, and heart rate monitor strap (with heart rate monitor) and weigh and take thermal image of them again:

Weight of subject with briefs and instrumentation (post wear test):	

☐	3) Allow subject to shower and have nurse conduct final checkup

Weight of water bottle before opening (g):	
Weight of water bottle after break(g):	

☐	4) Weigh equipment: Overall Weights (kg wet) : Individual Weights (kg wet):

Weight of gear:	

Underwear:	
T-shirt:	
Jacket:	
Pants:	
Socks:	
Gloves:	
Shoes:	
Belt:	
Helmet:	
HR monitor strap:	

IF FINAL TEST:	
☐	1) Email follow up survey to subject.

Appendix F: Physiological Wear Trial T-tests

KEY TO LABELS IN DETAILED DATA AND STATISTICAL OUTPUT

Garments
330 = 3.3 oz/yd^2 plain weave garment
770 = 7.7 oz/yd^2 twill weave garment
770+ = 7.7 oz/yd^2 twill weave garment with the alternate modacrylic/FR rayon blend base layer
950 = 9.5 oz/yd^2 plain weave garment
double = 6.0 oz/yd^2/ 7.5 oz/yd^2 double layer plain weave garment

Significant Statistical Differences
*** Significant at the 99% probability level
** Significant at the 95% probability level
* Significant at the 90% probability level
nsd Not significant at the 90% probability level

Core Temperature:

At 10 minutes:

330 vs 770 - 10 min		
t-Test: Paired Two Sample for Means		
	Variable 1	*Variable 2*
Mean	-0.02375	-0.04375
Variance	0.004284	0.002198
Observatic	8	8
Pearson Cc	0.390462	
Hypothesiz	0	
df	7	
t Stat	0.884995	
P(T<=t) on	0.202765	
t Critical o	1.894579	
P(T<=t) tw	0.405531	nsd
t Critical tv	2.364624	

330 vs. 770 +		
t-Test: Paired Two Sample for Means		
	Variable 1	*Variable 2*
Mean	-0.02375	-0.0375
Variance	0.004284	0.014536
Observatic	8	8
Pearson Cc	0.142565	
Hypothesiz	0	
df	7	
t Stat	0.302128	
P(T<=t) on	0.385667	
t Critical o	1.894579	
P(T<=t) tw	0.771334	nsd
t Critical tv	2.364624	

330 vs 950		
t-Test: Paired Two Sample for Means		
	Variable 1	*Variable 2*
Mean	-0.02375	-0.025
Variance	0.004284	0.004143
Observatic	8	8
Pearson Cc	0.001696	
Hypothesiz	0	
df	7	
t Stat	0.038547	
P(T<=t) on	0.485164	
t Critical o	1.894579	
P(T<=t) tw	0.970328	nsd
t Critical tv	2.364624	

330 vs. double		
t-Test: Paired Two Sample for Means		
	Variable 1	*Variable 2*
Mean	-0.02375	-0.075
Variance	0.004284	0.0074
Observatic	8	8
Pearson Cc	-0.36663	
Hypothesiz	0	
df	7	
t Stat	1.152759	
P(T<=t) on	0.143425	
t Critical o	1.894579	
P(T<=t) tw	0.28685	nsd
t Critical tv	2.364624	

770 vs 770 +		
t-Test: Paired Two Sample for Means		
	Variable 1	*Variable 2*
Mean	-0.04375	-0.0375
Variance	0.002198	0.014536
Observatic	8	8
Pearson Cc	-0.22303	
Hypothesiz	0	
df	7	
t Stat	-0.12739	
P(T<=t) on	0.451105	
t Critical o	1.894579	
P(T<=t) tw	0.902211	nsd
t Critical tv	2.364624	

770 vs. 950		
t-Test: Paired Two Sample for Means		
	Variable 1	*Variable 2*
Mean	-0.04375	-0.025
Variance	0.002198	0.004143
Observatic	8	8
Pearson Cc	0.243795	
Hypothesiz	0	
df	7	
t Stat	-0.75997	
P(T<=t) on	0.236043	
t Critical o	1.894579	
P(T<=t) tw	0.472086	nsd
t Critical tv	2.364624	

770 vs. double		
t-Test: Paired Two Sample for Means		
	Variable 1	*Variable 2*
Mean	-0.04375	-0.075
Variance	0.002198	0.0074
Observatic	8	8
Pearson Cc	-0.34889	
Hypothesiz	0	
df	7	
t Stat	0.793351	
P(T<=t) on	0.22681	
t Critical o	1.894579	
P(T<=t) tw	0.453621	nsd
t Critical tv	2.364624	

770 + vs. 950		
t-Test: Paired Two Sample for Means		
	Variable 1	*Variable 2*
Mean	-0.0375	-0.025
Variance	0.014536	0.004143
Observatic	8	8
Pearson Cc	0.491524	
Hypothesiz	0	
df	7	
t Stat	-0.33634	
P(T<=t) on	0.373237	
t Critical o	1.894579	
P(T<=t) tw	0.746475	nsd
t Critical tv	2.364624	

770 + vs. double		
t-Test: Paired Two Sample for Means		
	Variable 1	*Variable 2*
Mean	-0.0375	-0.075
Variance	0.014536	0.0074
Observatic	8	8
Pearson Cc	0.480721	
Hypothesiz	0	
df	7	
t Stat	0.96969	
P(T<=t) on	0.182252	
t Critical o	1.894579	
P(T<=t) tw	0.364505	nsd
t Critical tv	2.364624	

950 vs. double		
t-Test: Paired Two Sample for Means		
	Variable 1	*Variable 2*
Mean	-0.025	-0.075
Variance	0.004143	0.0074
Observatic	8	8
Pearson C(	0.368954	
Hypothesi:	0	
df	7	
t Stat	1.637679	
P(T<=t) on	0.07275	
t Critical o	1.894579	
P(T<=t) tw	0.1455	nsd
t Critical tv	2.364624	

At 30 min:

330 vs 770			330 vs. 770 +			330 vs 950		
t-Test: Paired Two Sample for Means			t-Test: Paired Two Sample for Means			t-Test: Paired Two Sample for Means		
	Variable 1	*Variable 2*		*Variable 1*	*Variable 2*		*Variable 1*	*Variable 2*
Mean	0.3	0.2775	Mean	0.3	0.2375	Mean	0.3	0.4125
Variance	0.021714	0.01645	Variance	0.021714	0.018964	Variance	0.021714	0.016479
Observatic	8	8	Observatic	8	8	Observatic	8	8
Pearson C(	0.034014		Pearson C(	-0.33861		Pearson C(	0.44331	
Hypothesi:	0		Hypothesi:	0		Hypothesi:	0	
df	7		df	7		df	7	
t Stat	0.331391		t Stat	0.757775		t Stat	-2.17407	
P(T<=t) on	0.375025		P(T<=t) on	0.23666		P(T<=t) on	0.033109	
t Critical o	1.894579		t Critical o	1.894579		t Critical o	1.894579	
P(T<=t) tw	0.750049	nsd	P(T<=t) tw	0.473319	nsd	P(T<=t) tw	0.066218	*
t Critical tv	2.364624		t Critical tv	2.364624		t Critical tv	2.364624	
330 vs. double			**770 vs 770 +**			**770 vs. 950**		
t-Test: Paired Two Sample for Means			t-Test: Paired Two Sample for Means			t-Test: Paired Two Sample for Means		
	Variable 1	*Variable 2*		*Variable 1*	*Variable 2*		*Variable 1*	*Variable 2*
Mean	0.3	0.3325	Mean	0.2775	0.2375	Mean	0.2775	0.4125
Variance	0.021714	0.01445	Variance	0.01645	0.018964	Variance	0.01645	0.016479
Observatic	8	8	Observatic	8	8	Observatic	8	8
Pearson C(	0.258881		Pearson C(	-0.10717		Pearson C(	0.303254	
Hypothesi:	0		Hypothesi:	0		Hypothesi:	0	
df	7		df	7		df	7	
t Stat	-0.5595		t Stat	0.571429		t Stat	-2.5209	
P(T<=t) on	0.29663		P(T<=t) on	0.29279		P(T<=t) on	0.019879	
t Critical o	1.894579		t Critical o	1.894579		t Critical o	1.894579	
P(T<=t) tw	0.59326	nsd	P(T<=t) tw	0.585581	nsd	P(T<=t) tw	0.039758	**
t Critical tv	2.364624		t Critical tv	2.364624		t Critical tv	2.364624	

770 vs. double

t-Test: Paired Two Sample for Means

	Variable 1	Variable 2
Mean	0.2775	0.3325
Variance	0.01645	0.01445
Observatic	8	8
Pearson Cc	-0.58884	
Hypothesiz	0	
df	7	
t Stat	-0.70235	
P(T<=t) on	0.252568	
t Critical o	1.894579	
P(T<=t) tw	0.505136	nsd
t Critical tv	2.364624	

770 + vs. 950

t-Test: Paired Two Sample for Means

	Variable 1	Variable 2
Mean	0.2375	0.4125
Variance	0.018964	0.016479
Observatic	8	8
Pearson Cc	-0.34062	
Hypothesiz	0	
df	7	
t Stat	-2.27144	
P(T<=t) on	0.028678	
t Critical o	1.894579	
P(T<=t) tw	0.057355	*
t Critical tv	2.364624	

770 + vs. double

t-Test: Paired Two Sample for Means

	Variable 1	Variable 2
Mean	0.2375	0.3
Variance	0.018964	0.021714
Observatic	8	8
Pearson Cc	-0.33861	
Hypothesiz	0	
df	7	
t Stat	-0.75777	
P(T<=t) on	0.23666	
t Critical o	1.894579	
P(T<=t) tw	0.473319	nsd
t Critical tv	2.364624	

950 vs. double

t-Test: Paired Two Sample for Means

	Variable 1	Variable 2
Mean	0.4125	0.3
Variance	0.016479	0.021714
Observatic	8	8
Pearson Cc	0.44331	
Hypothesiz	0	
df	7	
t Stat	2.174069	
P(T<=t) on	0.033109	
t Critical o	1.894579	
P(T<=t) tw	0.066218	*
t Critical tv	2.364624	

At 60 min:

330 vs 770

t-Test: Paired Two Sample for Means

	Variable 1	Variable 2
Mean	0.8725	0.68375
Variance	0.080336	0.052227
Observatic	8	8
Pearson Cc	0.384689	
Hypothesiz	0	
df	7	
t Stat	1.856132	
P(T<=t) on	0.052905	
t Critical o	1.894579	
P(T<=t) tw	0.105811	nsd
t Critical tv	2.364624	

330 vs. 770 +

t-Test: Paired Two Sample for Means

	Variable 1	Variable 2
Mean	0.8975	0.7875
Variance	0.061736	0.077136
Observatic	8	8
Pearson Cc	0.299657	
Hypothesiz	0	
df	7	
t Stat	0.996331	
P(T<=t) on	0.176138	
t Critical o	1.894579	
P(T<=t) tw	0.352276	nsd
t Critical tv	2.364624	

330 vs 950

t-Test: Paired Two Sample for Means

	Variable 1	Variable 2
Mean	0.8975	0.9575
Variance	0.061736	0.021307
Observatic	8	8
Pearson Cc	0.080944	
Hypothesiz	0	
df	7	
t Stat	-0.6109	
P(T<=t) on	0.280286	
t Critical o	1.894579	
P(T<=t) tw	0.560573	nsd
t Critical tv	2.364624	

330 vs. double

t-Test: Paired Two Sample for Means

	Variable 1	*Variable 2*
Mean	0.8975	0.96125
Variance	0.061736	0.039327
Observatic	8	8
Pearson Cc	0.673284	
Hypothesiz	0	
df	7	
t Stat	-0.96779	
P(T<=t) on	0.182694	
t Critical o	1.894579	
P(T<=t) tw	0.365388	nsd
t Critical tv	2.364624	

770 vs 770 +

t-Test: Paired Two Sample for Means

	Variable 1	*Variable 2*
Mean	0.68375	0.7875
Variance	0.052227	0.077136
Observatic	8	8
Pearson Cc	0.1674	
Hypothesiz	0	
df	7	
t Stat	-0.89247	
P(T<=t) on	0.200888	
t Critical o	1.894579	
P(T<=t) tw	0.401777	nsd
t Critical tv	2.364624	

770 vs. 950

t-Test: Paired Two Sample for Means

	Variable 1	*Variable 2*
Mean	0.68375	0.9575
Variance	0.052227	0.021307
Observatic	8	8
Pearson Cc	0.416576	
Hypothesiz	0	
df	7	
t Stat	-3.62031	
P(T<=t) on	0.004253	
t Critical o	1.894579	
P(T<=t) tw	0.008507	***
t Critical tv	2.364624	

770 vs. double

t-Test: Paired Two Sample for Means

	Variable 1	*Variable 2*
Mean	0.68375	0.96125
Variance	0.052227	0.039327
Observatic	8	8
Pearson Cc	0.218013	
Hypothesiz	0	
df	7	
t Stat	-2.92932	
P(T<=t) on	0.011023	
t Critical o	1.894579	
P(T<=t) tw	0.022045	**
t Critical tv	2.364624	

770 + vs. 950

t-Test: Paired Two Sample for Means

	Variable 1	*Variable 2*
Mean	0.7875	0.8975
Variance	0.077136	0.061736
Observatic	8	8
Pearson Cc	0.299657	
Hypothesiz	0	
df	7	
t Stat	-0.99633	
P(T<=t) on	0.176138	
t Critical o	1.894579	
P(T<=t) tw	0.352276	nsd
t Critical tv	2.364624	

770 + vs. double

t-Test: Paired Two Sample for Means

	Variable 1	*Variable 2*
Mean	0.7875	0.96125
Variance	0.077136	0.039327
Observatic	8	8
Pearson Cc	0.590405	
Hypothesiz	0	
df	7	
t Stat	-2.16708	
P(T<=t) on	0.033452	
t Critical o	1.894579	
P(T<=t) tw	0.066905	*
t Critical tv	2.364624	

950 vs. double

t-Test: Paired Two Sample for Means

	Variable 1	*Variable 2*
Mean	0.9575	0.96125
Variance	0.021307	0.039327
Observatic	8	8
Pearson Cc	0.351008	
Hypothesiz	0	
df	7	
t Stat	-0.05283	
P(T<=t) on	0.479673	
t Critical o	1.894579	
P(T<=t) tw	0.959346	nsd
t Critical tv	2.364624	

At 90 min:

330 vs 770		
t-Test: Paired Two Sample for Means		
	Variable 1	*Variable 2*
Mean	0.955	0.94875
Variance	0.081714	0.096555
Observatic	8	8
Pearson Cc	0.536285	
Hypothesi:	0	
df	7	
t Stat	0.061361	
P(T<=t) on	0.476394	
t Critical o	1.894579	
P(T<=t) tw	0.952787	nsd
t Critical tv	2.364624	

330 vs. 770 +		
t-Test: Paired Two Sample for Means		
	Variable 1	*Variable 2*
Mean	0.955	0.9
Variance	0.081714	0.126257
Observatic	8	8
Pearson Cc	0.29437	
Hypothesi:	0	
df	7	
t Stat	0.404134	
P(T<=t) on	0.349088	
t Critical o	1.894579	
P(T<=t) tw	0.698176	nsd
t Critical tv	2.364624	

330 vs 950		
t-Test: Paired Two Sample for Means		
	Variable 1	*Variable 2*
Mean	0.955	1.0425
Variance	0.081714	0.02805
Observatic	8	8
Pearson Cc	0.131889	
Hypothesi:	0	
df	7	
t Stat	-0.79408	
P(T<=t) on	0.226612	
t Critical o	1.894579	
P(T<=t) tw	0.453224	nsd
t Critical tv	2.364624	

330 vs. double		
t-Test: Paired Two Sample for Means		
	Variable 1	*Variable 2*
Mean	0.955	1.215
Variance	0.081714	0.066
Observatic	8	8
Pearson Cc	0.595254	
Hypothesi:	0	
df	7	
t Stat	-2.9951	
P(T<=t) on	0.01004	
t Critical o	1.894579	
P(T<=t) tw	0.020081	**
t Critical tv	2.364624	

770 vs 770 +		
t-Test: Paired Two Sample for Means		
	Variable 1	*Variable 2*
Mean	0.94875	0.9
Variance	0.096555	0.126257
Observatic	8	8
Pearson Cc	0.862225	
Hypothesi:	0	
df	7	
t Stat	0.765885	
P(T<=t) on	0.234389	
t Critical o	1.894579	
P(T<=t) tw	0.468778	nsd
t Critical tv	2.364624	

770 vs. 950		
t-Test: Paired Two Sample for Means		
	Variable 1	*Variable 2*
Mean	0.94875	1.0425
Variance	0.096555	0.02805
Observatic	8	8
Pearson Cc	0.692915	
Hypothesi:	0	
df	7	
t Stat	-1.15745	
P(T<=t) on	0.142526	
t Critical o	1.894579	
P(T<=t) tw	0.285052	nsd
t Critical tv	2.364624	

770 vs. double		
t-Test: Paired Two Sample for Means		
	Variable 1	*Variable 2*
Mean	0.94875	1.215
Variance	0.096555	0.066
Observatic	8	8
Pearson Cc	0.558963	
Hypothesi:	0	
df	7	
t Stat	-2.78129	
P(T<=t) on	0.013624	
t Critical o	1.894579	
P(T<=t) tw	0.027248	**
t Critical tv	2.364624	

770 + vs. 950		
t-Test: Paired Two Sample for Means		
	Variable 1	*Variable 2*
Mean	0.9	1.0425
Variance	0.126257	0.02805
Observatic	8	8
Pearson Cc	0.76553	
Hypothesi:	0	
df	7	
t Stat	-1.60334	
P(T<=t) on	0.076447	
t Critical o	1.894579	
P(T<=t) tw	0.152894	nsd
t Critical tv	2.364624	

770 + vs. double		
t-Test: Paired Two Sample for Means		
	Variable 1	*Variable 2*
Mean	0.9	1.215
Variance	0.126257	0.066
Observatic	8	8
Pearson Cc	0.465887	
Hypothesi:	0	
df	7	
t Stat	-2.72119	
P(T<=t) on	0.014857	
t Critical o	1.894579	
P(T<=t) tw	0.029715	**
t Critical tv	2.364624	

950 vs. double		
t-Test: Paired Two Sample for Means		
	Variable 1	*Variable 2*
Mean	1.0425	1.215
Variance	0.02805	0.066
Observatic	8	8
Pearson Cc	0.197884	
Hypothesiz	0	
df	7	
t Stat	-1.75804	
P(T<=t) on	0.061076	
t Critical o	1.894579	
P(T<=t) tw	0.122152	nsd
t Critical tv	2.364624	

At 120 min:

330 vs 770		
t-Test: Paired Two Sample for Means		
	Variable 1	*Variable 2*
Mean	1.14875	1.16875
Variance	0.094213	0.061898
Observatic	8	8
Pearson Cc	0.493472	
Hypothesiz	0	
df	7	
t Stat	-0.19908	
P(T<=t) on	0.42393	
t Critical o	1.894579	
P(T<=t) tw	0.847861	nsd
t Critical tv	2.364624	

330 vs. 770 +		
t-Test: Paired Two Sample for Means		
	Variable 1	*Variable 2*
Mean	1.14875	1.10875
Variance	0.094213	0.177384
Observatic	8	8
Pearson Cc	0.081098	
Hypothesiz	0	
df	7	
t Stat	0.22599	
P(T<=t) on	0.413833	
t Critical o	1.894579	
P(T<=t) tw	0.827666	nsd
t Critical tv	2.364624	

330 vs 950		
t-Test: Paired Two Sample for Means		
	Variable 1	*Variable 2*
Mean	1.14875	1.2775
Variance	0.094213	0.038136
Observatic	8	8
Pearson Cc	0.201807	
Hypothesiz	0	
df	7	
t Stat	-1.10731	
P(T<=t) on	0.152377	
t Critical o	1.894579	
P(T<=t) tw	0.304754	nsd
t Critical tv	2.364624	

330 vs. double		
t-Test: Paired Two Sample for Means		
	Variable 1	*Variable 2*
Mean	1.211429	1.537143
Variance	0.073248	0.07769
Observatic	7	7
Pearson Cc	0.252152	
Hypothesiz	0	
df	6	
t Stat	-2.56477	
P(T<=t) on	0.021317	
t Critical o	1.94318	
P(T<=t) tw	0.042634	**
t Critical tv	2.446912	

770 vs 770 +		
t-Test: Paired Two Sample for Means		
	Variable 1	*Variable 2*
Mean	1.16875	1.10875
Variance	0.061898	0.177384
Observatic	8	8
Pearson Cc	0.468565	
Hypothesiz	0	
df	7	
t Stat	0.451809	
P(T<=t) on	0.332537	
t Critical o	1.894579	
P(T<=t) tw	0.665073	nsd
t Critical tv	2.364624	

770 vs. 950		
t-Test: Paired Two Sample for Means		
	Variable 1	*Variable 2*
Mean	1.16875	1.2775
Variance	0.061898	0.038136
Observatic	8	8
Pearson Cc	-0.24883	
Hypothesiz	0	
df	7	
t Stat	-0.87275	
P(T<=t) on	0.205866	
t Critical o	1.894579	
P(T<=t) tw	0.411732	nsd
t Critical tv	2.364624	

770 vs. double		
t-Test: Paired Two Sample for Means		
	Variable 1	*Variable 2*
Mean	1.218571	1.537143
Variance	0.049048	0.07769
Observatic	7	7
Pearson Cc	-0.14074	
Hypothesiz	0	
df	6	
t Stat	-2.22025	
P(T<=t) on	0.034087	
t Critical o	1.94318	
P(T<=t) tw	0.068174	*
t Critical tv	2.446912	

770 + vs. 950		
t-Test: Paired Two Sample for Means		
	Variable 1	*Variable 2*
Mean	1.10875	1.2775
Variance	0.177384	0.038136
Observatic	8	8
Pearson Cc	0.443912	
Hypothesiz	0	
df	7	
t Stat	-1.2644	
P(T<=t) on	0.123279	
t Critical o	1.894579	
P(T<=t) tw	0.246557	nsd
t Critical tv	2.364624	

770 + vs. double		
t-Test: Paired Two Sample for Means		
	Variable 1	*Variable 2*
Mean	1.175714	1.537143
Variance	0.165095	0.07769
Observatic	7	7
Pearson Cc	0.240485	
Hypothesiz	0	
df	6	
t Stat	-2.20359	
P(T<=t) on	0.034878	
t Critical o	1.94318	
P(T<=t) tw	0.069757	*
t Critical tv	2.446912	

950 vs. double		
t-Test: Paired Two Sample for Means		
	Variable 1	*Variable 2*
Mean	1.282857	1.537143
Variance	0.044224	0.07769
Observatic	7	7
Pearson Cc	0.604952	
Hypothesiz	0	
df	6	
t Stat	-2.97924	
P(T<=t) on	0.01233	
t Critical o	1.94318	
P(T<=t) tw	0.024661	**
t Critical tv	2.446912	

At 140 min:

330 vs 770		
t-Test: Paired Two Sample for Means		
	Variable 1	*Variable 2*
Mean	0.92875	0.855
Variance	0.12427	0.068457
Observatic	8	8
Pearson Cc	0.524364	
Hypothesiz	0	
df	7	
t Stat	0.673249	
P(T<=t) on	0.261194	
t Critical o	1.894579	
P(T<=t) tw	0.522388	nsd
t Critical tv	2.364624	

330 vs. 770 +		
t-Test: Paired Two Sample for Means		
	Variable 1	*Variable 2*
Mean	0.92875	0.7975
Variance	0.12427	0.174707
Observatic	8	8
Pearson Cc	0.48581	
Hypothesiz	0	
df	7	
t Stat	0.940466	
P(T<=t) on	0.189145	
t Critical o	1.894579	
P(T<=t) tw	0.378291	nsd
t Critical tv	2.364624	

330 vs 950		
t-Test: Paired Two Sample for Means		
	Variable 1	*Variable 2*
Mean	0.92875	0.99
Variance	0.12427	0.067429
Observatic	8	8
Pearson Cc	0.309939	
Hypothesiz	0	
df	7	
t Stat	-0.47158	
P(T<=t) on	0.325786	
t Critical o	1.894579	
P(T<=t) tw	0.651571	nsd
t Critical tv	2.364624	

330 vs. double

t-Test: Paired Two Sample for Means

	Variable 1	Variable 2	
Mean	1.011429	1.175714	
Variance	0.081181	0.058995	
Observatic	7	7	
Pearson Cc	0.20481		
Hypothesiz	0		
df	6		
t Stat	-1.29979		
P(T<=t) on	0.120687		
t Critical o	1.94318		
P(T<=t) tw	0.241373	nsd	
t Critical tv	2.446912		

770 vs 770 +

t-Test: Paired Two Sample for Means

	Variable 1	Variable 2	
Mean	0.855	0.7975	
Variance	0.068457	0.174707	
Observatic	8	8	
Pearson Cc	0.547594		
Hypothesiz	0		
df	7		
t Stat	0.462986		
P(T<=t) on	0.328712		
t Critical o	1.894579		
P(T<=t) tw	0.657424	nsd	
t Critical tv	2.364624		

770 vs. 950

t-Test: Paired Two Sample for Means

	Variable 1	Variable 2	
Mean	0.855	0.99	
Variance	0.068457	0.067429	
Observatic	8	8	
Pearson Cc	0.02355		
Hypothesiz	0		
df	7		
t Stat	-1.04825		
P(T<=t) on	0.16468		
t Critical o	1.894579		
P(T<=t) tw	0.32936	nsd	
t Critical tv	2.364624		

770 vs. double

t-Test: Paired Two Sample for Means

	Variable 1	Variable 2	
Mean	0.928571	1.175714	
Variance	0.029348	0.058995	
Observatic	7	7	
Pearson Cc	-0.01659		
Hypothesiz	0		
df	6		
t Stat	-2.18295		
P(T<=t) on	0.035885		
t Critical o	1.94318		
P(T<=t) tw	0.071769	*	
t Critical tv	2.446912		

770 + vs. 950

t-Test: Paired Two Sample for Means

	Variable 1	Variable 2	
Mean	0.7975	0.99	
Variance	0.174707	0.067429	
Observatic	8	8	
Pearson Cc	0.683244		
Hypothesiz	0		
df	7		
t Stat	-1.77756		
P(T<=t) on	0.059359		
t Critical o	1.894579		
P(T<=t) tw	0.118717	nsd	
t Critical tv	2.364624		

770 + vs. double

t-Test: Paired Two Sample for Means

	Variable 1	Variable 2	
Mean	0.885714	1.175714	
Variance	0.131195	0.058995	
Observatic	7	7	
Pearson Cc	0.476019		
Hypothesiz	0		
df	6		
t Stat	-2.35184		
P(T<=t) on	0.028457		
t Critical o	1.94318		
P(T<=t) tw	0.056915	*	
t Critical tv	2.446912		

950 vs. double

t-Test: Paired Two Sample for Means

	Variable 1	Variable 2	
Mean	1.005714	1.175714	
Variance	0.076362	0.058995	
Observatic	7	7	
Pearson Cc	0.83352		
Hypothesiz	0		
df	6		
t Stat	-2.93611		
P(T<=t) on	0.01304		
t Critical o	1.94318		
P(T<=t) tw	0.026079	**	
t Critical tv	2.446912		

At maximum rise in core temperature:

330 vs 770

t-Test: Paired Two Sample for Means

	Variable 1	*Variable 2*
Mean	1.165	1.22625
Variance	0.100771	0.075284
Observatic	8	8
Pearson Cc	0.45555	
Hypothesi:	0	
df	7	
t Stat	-0.55711	
P(T<=t) on	0.297404	
t Critical o	1.894579	
P(T<=t) tw	0.594808	nsd
t Critical tv	2.364624	

330 vs 770+

t-Test: Paired Two Sample for Means

	Variable 1	*Variable 2*
Mean	1.165	1.1225
Variance	0.100771	0.176421
Observatic	8	8
Pearson Cc	0.104891	
Hypothesi:	0	
df	7	
t Stat	0.240792	
P(T<=t) on	0.408309	
t Critical o	1.894579	
P(T<=t) tw	0.816617	nsd
t Critical tv	2.364624	

330 vs 950

t-Test: Paired Two Sample for Means

	Variable 1	*Variable 2*
Mean	1.165	1.2925
Variance	0.100771	0.037993
Observatic	8	8
Pearson Cc	0.226491	
Hypothesi:	0	
df	7	
t Stat	-1.08371	
P(T<=t) on	0.157202	
t Critical o	1.894579	
P(T<=t) tw	0.314405	nsd
t Critical tv	2.364624	

330 vs double

t-Test: Paired Two Sample for Means

	Variable 1	*Variable 2*
Mean	1.165	1.555
Variance	0.100771	0.071686
Observatic	8	8
Pearson Cc	0.329269	
Hypothesi:	0	
df	7	
t Stat	-3.23201	
P(T<=t) on	0.007206	
t Critical o	1.894579	
P(T<=t) tw	0.014411	**
t Critical tv	2.364624	

770 vs 770+

t-Test: Paired Two Sample for Means

	Variable 1	*Variable 2*
Mean	1.22625	1.1225
Variance	0.075284	0.176421
Observatic	8	8
Pearson Cc	0.472126	
Hypothesi:	0	
df	7	
t Stat	0.776321	
P(T<=t) on	0.231489	
t Critical o	1.894579	
P(T<=t) tw	0.462979	nsd
t Critical tv	2.364624	

770 vs 950

t-Test: Paired Two Sample for Means

	Variable 1	*Variable 2*
Mean	1.22625	1.2925
Variance	0.075284	0.037993
Observatic	8	8
Pearson Cc	-0.22017	
Hypothesi:	0	
df	7	
t Stat	-0.50658	
P(T<=t) on	0.314007	
t Critical o	1.894579	
P(T<=t) tw	0.628014	nsd
t Critical tv	2.364624	

770 vs double

t-Test: Paired Two Sample for Means

	Variable 1	*Variable 2*
Mean	1.22625	1.555
Variance	0.075284	0.071686
Observatic	8	8
Pearson Cc	0.0948	
Hypothesi:	0	
df	7	
t Stat	-2.54928	
P(T<=t) on	0.019072	
t Critical o	1.894579	
P(T<=t) tw	0.038144	**
t Critical tv	2.364624	

770+ vs 950

t-Test: Paired Two Sample for Means

	Variable 1	*Variable 2*
Mean	1.1225	1.2925
Variance	0.176421	0.037993
Observatic	8	8
Pearson Cc	0.480289	
Hypothesi:	0	
df	7	
t Stat	-1.30494	
P(T<=t) on	0.116586	
t Critical o	1.894579	
P(T<=t) tw	0.233172	nsd
t Critical tv	2.364624	

770+ vs double

t-Test: Paired Two Sample for Means

	Variable 1	*Variable 2*
Mean	1.1225	1.555
Variance	0.176421	0.071686
Observatic	8	8
Pearson Cc	0.41844	
Hypothesi:	0	
df	7	
t Stat	-3.11732	
P(T<=t) on	0.008454	
t Critical o	1.894579	
P(T<=t) tw	0.016907	**
t Critical tv	2.364624	

950 vs double		
t-Test: Paired Two Sample for Means		
	Variable 1	*Variable 2*
Mean	1.2925	1.555
Variance	0.037993	0.071686
Observatio	8	8
Pearson Co	0.541727	
Hypothesiz	0	
df	7	
t Stat	-3.22093	
P(T<=t) on	0.007317	
t Critical o	1.894579	
P(T<=t) tw	0.014635	**
t Critical tw	2.364624	

Heart Rate:

At Maximum Change in Heart Rate:

330 vs 770			
t-Test: Paired Two Sample for Means			
	Variable 1	Variable 2	
Mean	76.2125	76.1625	
Variance	370.0898	319.7798	
Observatic	8	8	
Pearson C	0.696808		
Hypothesi:	0		
df	7		
t Stat	0.009749		
P(T<=t) on	0.496247		
t Critical o	1.894579		
P(T<=t) tw	0.992494	nsd	
t Critical tv	2.364624		

330 vs 770+			
t-Test: Paired Two Sample for Means			
	Variable 1	Variable 2	
Mean	76.2125	73.9	
Variance	370.0898	392.9771	
Observatic	8	8	
Pearson C	0.614291		
Hypothesi:	0		
df	7		
t Stat	0.381118		
P(T<=t) on	0.357209		
t Critical o	1.894579		
P(T<=t) tw	0.714419	nsd	
t Critical tv	2.364624		

330 vs 950			
t-Test: Paired Two Sample for Means			
	Variable 1	Variable 2	
Mean	76.2125	71.6375	
Variance	370.0898	1351.703	
Observatic	8	8	
Pearson C	0.559443		
Hypothesi:	0		
df	7		
t Stat	0.424225		
P(T<=t) on	0.342067		
t Critical o	1.894579		
P(T<=t) tw	0.684135	nsd	
t Critical tv	2.364624		

330 vs double			
t-Test: Paired Two Sample for Means			
	Variable 1	Variable 2	
Mean	76.2125	85.025	
Variance	370.0898	372.8679	
Observatic	8	8	
Pearson C	0.91317		
Hypothesi:	0		
df	7		
t Stat	-3.10322		
P(T<=t) on	0.008622		
t Critical o	1.894579		
P(T<=t) tw	0.017244	**	
t Critical tv	2.364624		

770 vs 770+			
t-Test: Paired Two Sample for Means			
	Variable 1	Variable 2	
Mean	76.1625	73.9	
Variance	319.7798	392.9771	
Observatic	8	8	
Pearson C	0.912362		
Hypothesi:	0		
df	7		
t Stat	0.788283		
P(T<=t) on	0.228196		
t Critical o	1.894579		
P(T<=t) tw	0.456392	nsd	
t Critical tv	2.364624		

770 vs 950			
t-Test: Paired Two Sample for Means			
	Variable 1	Variable 2	
Mean	76.1625	71.6375	
Variance	319.7798	1351.703	
Observatic	8	8	
Pearson C	0.757705		
Hypothesi:	0		
df	7		
t Stat	0.492558		
P(T<=t) on	0.318698		
t Critical o	1.894579		
P(T<=t) tw	0.637397	nsd	
t Critical tv	2.364624		

770 vs double			
t-Test: Paired Two Sample for Means			
	Variable 1	Variable 2	
Mean	76.1625	85.025	
Variance	319.7798	372.8679	
Observatic	8	8	
Pearson C	0.636024		
Hypothesi:	0		
df	7		
t Stat	-1.57469		
P(T<=t) on	0.079664		
t Critical o	1.894579		
P(T<=t) tw	0.159329	nsd	
t Critical tv	2.364624		

770+ vs 950			
t-Test: Paired Two Sample for Means			
	Variable 1	Variable 2	
Mean	73.9	71.6375	
Variance	392.9771	1351.703	
Observatic	8	8	
Pearson C	0.573579		
Hypothesi:	0		
df	7		
t Stat	0.212299		
P(T<=t) on	0.418962		
t Critical o	1.894579		
P(T<=t) tw	0.837924	nsd	
t Critical tv	2.364624		

770+ vs double			
t-Test: Paired Two Sample for Means			
	Variable 1	Variable 2	
Mean	73.9	85.025	
Variance	392.9771	372.8679	
Observatic	8	8	
Pearson C	0.567375		
Hypothesi:	0		
df	7		
t Stat	-1.72831		
P(T<=t) on	0.063782		
t Critical o	1.894579		
P(T<=t) tw	0.127565	nsd	
t Critical tv	2.364624		

950 vs double		
t-Test: Paired Two Sample for Means		
	Variable 1	*Variable 2*
Mean	71.6375	85.025
Variance	1351.703	372.8679
Observatic	8	8
Pearson C(	0.57414	
Hypothesi:	0	
df	7	
t Stat	-1.25567	
P(T<=t) on	0.124762	
t Critical o	1.894579	
P(T<=t) tw	0.249525	nsd
t Critical tv	2.364624	

Physiological Strain Index (PSI):

At Maximum Change in Physiological Strain Index (PSI):

330 vs 770

t-Test: Paired Two Sample for Means

	Variable 1	Variable 2
Mean	5.363902	5.600042
Variance	0.288814	0.766029
Observatic	8	8
Pearson C(	0.866779	
Hypothesi:	0	
df	7	
t Stat	-1.36494	
P(T<=t) on	0.107261	
t Critical o	1.894579	
P(T<=t) tw	0.214521	nsd
t Critical tv	2.364624	

330 vs 770+

t-Test: Paired Two Sample for Means

	Variable 1	Variable 2
Mean	5.363902	5.290172
Variance	0.288814	2.009183
Observatic	8	8
Pearson C(	0.656306	
Hypothesi:	0	
df	7	
t Stat	0.183036	
P(T<=t) on	0.429979	
t Critical o	1.894579	
P(T<=t) tw	0.859959	nsd
t Critical tv	2.364624	

330 vs 950

t-Test: Paired Two Sample for Means

	Variable 1	Variable 2
Mean	5.363902	5.285878
Variance	0.288814	5.625647
Observatic	8	8
Pearson C(	0.227871	
Hypothesi:	0	
df	7	
t Stat	0.095558	
P(T<=t) on	0.463275	
t Critical o	1.894579	
P(T<=t) tw	0.92655	nsd
t Critical tv	2.364624	

330 vs double

t-Test: Paired Two Sample for Means

	Variable 1	Variable 2
Mean	5.363902	6.528502
Variance	0.288814	1.077603
Observatic	8	8
Pearson C(	0.47244	
Hypothesi:	0	
df	7	
t Stat	-3.59555	
P(T<=t) on	0.004396	
t Critical o	1.894579	
P(T<=t) tw	0.008792	***
t Critical tv	2.364624	

770 vs 770+

t-Test: Paired Two Sample for Means

	Variable 1	Variable 2
Mean	5.600042	5.290172
Variance	0.766029	2.009183
Observatic	8	8
Pearson C(	0.930593	
Hypothesi:	0	
df	7	
t Stat	1.283596	
P(T<=t) on	0.120069	
t Critical o	1.894579	
P(T<=t) tw	0.240138	nsd
t Critical tv	2.364624	

770 vs 950

t-Test: Paired Two Sample for Means

	Variable 1	Variable 2
Mean	5.600042	5.285878
Variance	0.766029	5.625647
Observatic	8	8
Pearson C(	0.485428	
Hypothesi:	0	
df	7	
t Stat	0.424766	
P(T<=t) on	0.341879	
t Critical o	1.894579	
P(T<=t) tw	0.683758	nsd
t Critical tv	2.364624	

770 vs double

t-Test: Paired Two Sample for Means

	Variable 1	Variable 2
Mean	5.600042	6.528502
Variance	0.766029	1.077603
Observatic	8	8
Pearson C(	0.42168	
Hypothesi:	0	
df	7	
t Stat	-2.53001	
P(T<=t) on	0.019616	
t Critical o	1.894579	
P(T<=t) tw	0.039233	**
t Critical tv	2.364624	

770+ vs 950

t-Test: Paired Two Sample for Means

	Variable 1	Variable 2
Mean	5.290172	5.285878
Variance	2.009183	5.625647
Observatic	8	8
Pearson C(	0.539681	
Hypothesi:	0	
df	7	
t Stat	0.006068	
P(T<=t) on	0.497664	
t Critical o	1.894579	
P(T<=t) tw	0.995328	nsd
t Critical tv	2.364624	

770+ vs double

t-Test: Paired Two Sample for Means

	Variable 1	Variable 2
Mean	5.290172	6.528502
Variance	2.009183	1.077603
Observatic	8	8
Pearson C(	0.431143	
Hypothesi:	0	
df	7	
t Stat	-2.59768	
P(T<=t) on	0.017773	
t Critical o	1.894579	
P(T<=t) tw	0.035545	**
t Critical tv	2.364624	

950 vs double		
t-Test: Paired Two Sample for Means		
	Variable 1	*Variable 2*
Mean	5.285878	6.528502
Variance	5.625647	1.077603
Observatio	8	8
Pearson C	0.490059	
Hypothesi	0	
df	7	
t Stat	-1.69689	
P(T<=t) on	0.066765	
t Critical o	1.894579	
P(T<=t) tw	0.133531	nsd
t Critical tv	2.364624	

Chest Skin Temperature:

At 65 min:

330 vs 770		
t-Test: Paired Two Sample for Means		
	Variable 1	*Variable 2*
Mean	4.19625	4.32875
Variance	1.854541	1.471098
Observatic	8	8
Pearson C	0.47286	
Hypothesi:	0	
df	7	
t Stat	-0.28221	
P(T<=t) on	0.392974	
t Critical o	1.894579	
P(T<=t) tw	0.785948	nsd
t Critical tv	2.364624	

330 vs 770+		
t-Test: Paired Two Sample for Means		
	Variable 1	*Variable 2*
Mean	4.19625	3.55375
Variance	1.854541	1.700398
Observatic	8	8
Pearson C	0.777293	
Hypothesi:	0	
df	7	
t Stat	2.039031	
P(T<=t) on	0.040414	
t Critical o	1.894579	
P(T<=t) tw	0.080828	*
t Critical tv	2.364624	

330 vs 950		
t-Test: Paired Two Sample for Means		
	Variable 1	*Variable 2*
Mean	4.19625	4.215
Variance	1.854541	2.206143
Observatic	8	8
Pearson C	0.612271	
Hypothesi:	0	
df	7	
t Stat	-0.04214	
P(T<=t) on	0.483782	
t Critical o	1.894579	
P(T<=t) tw	0.967564	nsd
t Critical tv	2.364624	

330 vs double		
t-Test: Paired Two Sample for Means		
	Variable 1	*Variable 2*
Mean	4.19625	4.57625
Variance	1.854541	0.984598
Observatic	8	8
Pearson C	0.721173	
Hypothesi:	0	
df	7	
t Stat	-1.13922	
P(T<=t) on	0.146046	
t Critical o	1.894579	
P(T<=t) tw	0.292093	nsd
t Critical tv	2.364624	

770 vs 770+		
t-Test: Paired Two Sample for Means		
	Variable 1	*Variable 2*
Mean	4.32875	3.55375
Variance	1.471098	1.700398
Observatic	8	8
Pearson C	0.43404	
Hypothesi:	0	
df	7	
t Stat	1.634505	
P(T<=t) on	0.073084	
t Critical o	1.894579	
P(T<=t) tw	0.146169	nsd
t Critical tv	2.364624	

770 vs 950		
t-Test: Paired Two Sample for Means		
	Variable 1	*Variable 2*
Mean	4.32875	4.215
Variance	1.471098	2.206143
Observatic	8	8
Pearson C	0.814628	
Hypothesi:	0	
df	7	
t Stat	0.373475	
P(T<=t) on	0.359924	
t Critical o	1.894579	
P(T<=t) tw	0.719849	nsd
t Critical tv	2.364624	

770 vs double		
t-Test: Paired Two Sample for Means		
	Variable 1	*Variable 2*
Mean	4.32875	4.57625
Variance	1.471098	0.984598
Observatic	8	8
Pearson C	0.745302	
Hypothesi:	0	
df	7	
t Stat	-0.86055	
P(T<=t) on	0.20899	
t Critical o	1.894579	
P(T<=t) tw	0.417981	nsd
t Critical tv	2.364624	

770+ vs 950		
t-Test: Paired Two Sample for Means		
	Variable 1	*Variable 2*
Mean	3.55375	4.215
Variance	1.700398	2.206143
Observatic	8	8
Pearson C	0.818357	
Hypothesi:	0	
df	7	
t Stat	-2.17934	
P(T<=t) on	0.032852	
t Critical o	1.894579	
P(T<=t) tw	0.065705	*
t Critical tv	2.364624	

770+ vs double		
t-Test: Paired Two Sample for Means		
	Variable 1	*Variable 2*
Mean	3.55375	4.57625
Variance	1.700398	0.984598
Observatic	8	8
Pearson C	0.870628	
Hypothesi:	0	
df	7	
t Stat	-4.40032	
P(T<=t) on	0.001578	
t Critical o	1.894579	
P(T<=t) tw	0.003156	***
t Critical tv	2.364624	

950 vs double		
t-Test: Paired Two Sample for Means		
	Variable 1	*Variable 2*
Mean	4.215	4.57625
Variance	2.206143	0.984598
Observatio	8	8
Pearson Co	0.930081	
Hypothesiz	0	
df	7	
t Stat	-1.52455	
P(T<=t) on	0.085599	
t Critical o	1.894579	
P(T<=t) tw	0.171198	nsd
t Critical tv	2.364624	

At 120 min:

330 vs 770		
t-Test: Paired Two Sample for Means		
	Variable 1	*Variable 2*
Mean	3.55875	3.53375
Variance	1.773441	1.231284
Observatio	8	8
Pearson Co	0.442495	
Hypothesiz	0	
df	7	
t Stat	0.054281	
P(T<=t) on	0.479114	
t Critical o	1.894579	
P(T<=t) tw	0.958228	nsd
t Critical tv	2.364624	

330 vs 770+		
t-Test: Paired Two Sample for Means		
	Variable 1	*Variable 2*
Mean	3.55875	3.2825
Variance	1.773441	1.809536
Observatio	8	8
Pearson Co	0.91997	
Hypothesiz	0	
df	7	
t Stat	1.458722	
P(T<=t) on	0.094003	
t Critical o	1.894579	
P(T<=t) tw	0.188005	nsd
t Critical tv	2.364624	

330 vs 950		
t-Test: Paired Two Sample for Means		
	Variable 1	*Variable 2*
Mean	3.85875	3.2825
Variance	1.643927	1.809536
Observatio	8	8
Pearson Co	0.76491	
Hypothesiz	0	
df	7	
t Stat	1.805512	
P(T<=t) on	0.056981	
t Critical o	1.894579	
P(T<=t) tw	0.113961	nsd
t Critical tv	2.364624	

330 vs double		
t-Test: Paired Two Sample for Means		
	Variable 1	*Variable 2*
Mean	3.85875	4.12375
Variance	1.643927	1.337255
Observatio	8	8
Pearson Co	0.793054	
Hypothesiz	0	
df	7	
t Stat	-0.94471	
P(T<=t) on	0.188133	
t Critical o	1.894579	
P(T<=t) tw	0.376265	nsd
t Critical tv	2.364624	

770 vs 770+		
t-Test: Paired Two Sample for Means		
	Variable 1	*Variable 2*
Mean	3.53375	3.2825
Variance	1.231284	1.809536
Observatio	8	8
Pearson Co	0.596615	
Hypothesiz	0	
df	7	
t Stat	0.633159	
P(T<=t) on	0.273375	
t Critical o	1.894579	
P(T<=t) tw	0.54675	nsd
t Critical tv	2.364624	

770 vs 950		
t-Test: Paired Two Sample for Means		
	Variable 1	*Variable 2*
Mean	3.53375	3.85875
Variance	1.231284	1.643927
Observatio	8	8
Pearson Co	0.739582	
Hypothesiz	0	
df	7	
t Stat	-1.04705	
P(T<=t) on	0.16494	
t Critical o	1.894579	
P(T<=t) tw	0.32988	nsd
t Critical tv	2.364624	

770 vs double		
t-Test: Paired Two Sample for Means		
	Variable 1	*Variable 2*
Mean	3.53375	4.12375
Variance	1.231284	1.337255
Observatic	8	8
Pearson Cc	0.657174	
Hypothesi:	0	
df	7	
t Stat	-1.7769	
P(T<=t) on	0.059416	
t Critical o	1.894579	
P(T<=t) tw	0.118832	nsd
t Critical tv	2.364624	

770+ vs 950		
t-Test: Paired Two Sample for Means		
	Variable 1	*Variable 2*
Mean	3.2825	3.85875
Variance	1.809536	1.643927
Observatic	8	8
Pearson Cc	0.76491	
Hypothesi:	0	
df	7	
t Stat	-1.80551	
P(T<=t) on	0.056981	
t Critical o	1.894579	
P(T<=t) tw	0.113961	nsd
t Critical tv	2.364624	

770+ vs double		
t-Test: Paired Two Sample for Means		
	Variable 1	*Variable 2*
Mean	3.2825	4.12375
Variance	1.809536	1.337255
Observatic	8	8
Pearson Cc	0.869667	
Hypothesi:	0	
df	7	
t Stat	-3.58252	
P(T<=t) on	0.004473	
t Critical o	1.894579	
P(T<=t) tw	0.008946	***
t Critical tv	2.364624	

950 vs double		
t-Test: Paired Two Sample for Means		
	Variable 1	*Variable 2*
Mean	3.85875	4.12375
Variance	1.643927	1.337255
Observatic	8	8
Pearson Cc	0.793054	
Hypothesi:	0	
df	7	
t Stat	-0.94471	
P(T<=t) on	0.188133	
t Critical o	1.894579	
P(T<=t) tw	0.376265	nsd
t Critical tv	2.364624	

At the maximum rise in chest skin temperature:

330 vs 770		
t-Test: Paired Two Sample for Means		
	Variable 1	*Variable 2*
Mean	4.8325	4.81625
Variance	1.005621	0.784141
Observatic	8	8
Pearson Cc	0.159133	
Hypothesi:	0	
df	7	
t Stat	0.037439	
P(T<=t) on	0.48559	
t Critical o	1.894579	
P(T<=t) tw	0.97118	nsd
t Critical tv	2.364624	

330 vs 770+		
t-Test: Paired Two Sample for Means		
	Variable 1	*Variable 2*
Mean	4.8325	4.64375
Variance	1.005621	0.867741
Observatic	8	8
Pearson Cc	0.79057	
Hypothesi:	0	
df	7	
t Stat	0.847988	
P(T<=t) on	0.212244	
t Critical o	1.894579	
P(T<=t) tw	0.424488	nsd
t Critical tv	2.364624	

330 vs 950		
t-Test: Paired Two Sample for Means		
	Variable 1	*Variable 2*
Mean	4.8325	4.71125
Variance	1.005621	1.264698
Observatic	8	8
Pearson Cc	0.356169	
Hypothesi:	0	
df	7	
t Stat	0.283148	
P(T<=t) on	0.392627	
t Critical o	1.894579	
P(T<=t) tw	0.785254	nsd
t Critical tv	2.364624	

330 vs double

t-Test: Paired Two Sample for Means

	Variable 1	Variable 2	
Mean	4.8325	5.01875	
Variance	1.005621	1.17987	
Observatic	8	8	
Pearson Cc	0.642414		
Hypothesiz	0		
df	7		
t Stat	-0.59421		
P(T<=t) on	0.285535		
t Critical o	1.894579		
P(T<=t) tw	0.57107	nsd	
t Critical tv	2.364624		

770 vs 770+

t-Test: Paired Two Sample for Means

	Variable 1	Variable 2	
Mean	4.81625	4.64375	
Variance	0.784141	0.867741	
Observatic	8	8	
Pearson Cc	0.185258		
Hypothesiz	0		
df	7		
t Stat	0.420505		
P(T<=t) on	0.343362		
t Critical o	1.894579		
P(T<=t) tw	0.686725	nsd	
t Critical tv	2.364624		

770 vs 950

t-Test: Paired Two Sample for Means

	Variable 1	Variable 2	
Mean	4.81625	4.71125	
Variance	0.784141	1.264698	
Observatic	8	8	
Pearson Cc	0.574422		
Hypothesiz	0		
df	7		
t Stat	0.312223		
P(T<=t) on	0.381983		
t Critical o	1.894579		
P(T<=t) tw	0.763966	nsd	
t Critical tv	2.364624		

770 vs double

t-Test: Paired Two Sample for Means

	Variable 1	Variable 2	
Mean	4.81625	5.01875	
Variance	0.784141	1.17987	
Observatic	8	8	
Pearson Cc	0.662443		
Hypothesiz	0		
df	7		
t Stat	-0.68969		
P(T<=t) on	0.256298		
t Critical o	1.894579		
P(T<=t) tw	0.512595	nsd	
t Critical tv	2.364624		

770+ vs 950

t-Test: Paired Two Sample for Means

	Variable 1	Variable 2	
Mean	4.64375	4.71125	
Variance	0.867741	1.264698	
Observatic	8	8	
Pearson Cc	0.681564		
Hypothesiz	0		
df	7		
t Stat	-0.22747		
P(T<=t) on	0.41328		
t Critical o	1.894579		
P(T<=t) tw	0.826559	nsd	
t Critical tv	2.364624		

770+ vs double

t-Test: Paired Two Sample for Means

	Variable 1	Variable 2	
Mean	4.64375	5.01875	
Variance	0.867741	1.17987	
Observatic	8	8	
Pearson Cc	0.851142		
Hypothesiz	0		
df	7		
t Stat	-1.86003		
P(T<=t) on	0.052603		
t Critical o	1.894579		
P(T<=t) tw	0.105207	nsd	
t Critical tv	2.364624		

950 vs double

t-Test: Paired Two Sample for Means

	Variable 1	Variable 2	
Mean	4.71125	5.01875	
Variance	1.264698	1.17987	
Observatic	8	8	
Pearson Cc	0.869414		
Hypothesiz	0		
df	7		
t Stat	-1.53628		
P(T<=t) on	0.084175		
t Critical o	1.894579		
P(T<=t) tw	0.168349	nsd	
t Critical tv	2.364624		

Back Skin Temperature:

At 120 min:

330 vs 770

t-Test: Paired Two Sample for Means

	Variable 1	Variable 2	
Mean	5.70125	5.23375	
Variance	8.296098	3.359541	
Observatic	8	8	
Pearson Cc	0.776935		
Hypothesi:	0		
df	7		
t Stat	0.711662		
P(T<=t) on	0.249849		
t Critical o	1.894579		
P(T<=t) tw	0.499697	nsd	
t Critical tv	2.364624		

330 vs 770+

t-Test: Paired Two Sample for Means

	Variable 1	Variable 2	
Mean	5.70125	4.14	
Variance	8.296098	3.099029	
Observatic	8	8	
Pearson Cc	0.614353		
Hypothesi:	0		
df	7		
t Stat	1.943045		
P(T<=t) on	0.046558		
t Critical o	1.894579		
P(T<=t) tw	0.093116	*	
t Critical tv	2.364624		

330 vs 950

t-Test: Paired Two Sample for Means

	Variable 1	Variable 2	
Mean	5.70125	5.30625	
Variance	8.296098	3.882627	
Observatic	8	8	
Pearson Cc	0.822321		
Hypothesi:	0		
df	7		
t Stat	0.66241		
P(T<=t) on	0.264453		
t Critical o	1.894579		
P(T<=t) tw	0.528907	nsd	
t Critical tv	2.364624		

330 vs double

t-Test: Two-Sample Assuming Unequal Varia

	Variable 1	Variable 2	
Mean	5.70125	3.592857	
Variance	8.296098	1.233157	
Observatic	8	7	
Hypothesi:	0		
df	9		
t Stat	1.914209		
P(T<=t) on	0.043934		
t Critical o	1.833113		
P(T<=t) tw	0.087868	*	
t Critical tv	2.262157		

770 vs 770+

t-Test: Paired Two Sample for Means

	Variable 1	Variable 2	
Mean	5.23375	4.14	
Variance	3.359541	3.099029	
Observatic	8	8	
Pearson Cc	0.564667		
Hypothesi:	0		
df	7		
t Stat	1.843974		
P(T<=t) on	0.053858		
t Critical o	1.894579		
P(T<=t) tw	0.107715	nsd	
t Critical tv	2.364624		

770 vs 950

t-Test: Paired Two Sample for Means

	Variable 1	Variable 2	
Mean	5.23375	5.30625	
Variance	3.359541	3.882627	
Observatic	8	8	
Pearson Cc	0.871179		
Hypothesi:	0		
df	7		
t Stat	-0.21045		
P(T<=t) on	0.419655		
t Critical o	1.894579		
P(T<=t) tw	0.83931	nsd	
t Critical tv	2.364624		

770 vs double

t-Test: Two-Sample Assuming Unequal Varia

	Variable 1	Variable 2	
Mean	5.23375	3.592857	
Variance	3.359541	1.233157	
Observatic	8	7	
Hypothesi:	0		
df	12		
t Stat	2.125288		
P(T<=t) on	0.027507		
t Critical o	1.782288		
P(T<=t) tw	0.055015	*	
t Critical tv	2.178813		

770+ vs 950

t-Test: Paired Two Sample for Means

	Variable 1	Variable 2	
Mean	4.14	5.30625	
Variance	3.099029	3.882627	
Observatic	8	8	
Pearson Cc	0.881288		
Hypothesi:	0		
df	7		
t Stat	-3.54124		
P(T<=t) on	0.004727		
t Critical o	1.894579		
P(T<=t) tw	0.009454	***	
t Critical tv	2.364624		

770+ vs double

t-Test: Two-Sample Assuming Unequal Varia

	Variable 1	Variable 2	
Mean	4.14	3.592857	
Variance	3.099029	1.233157	
Observatic	8	7	
Hypothesi:	0		
df	12		
t Stat	0.728848		
P(T<=t) on	0.240039		
t Critical o	1.782288		
P(T<=t) tw	0.480078	nsd	
t Critical tv	2.178813		

950 vs double		
t-Test: Two-Sample Assuming Unequal Variances		
	Variable 1	Variable 2
Mean	5.30625	3.592857
Variance	3.882627	1.233157
Observatic	8	7
Hypothesi:	0	
df	11	
t Stat	2.106658	
P(T<=t) on	0.029458	
t Critical o	1.795885	
P(T<=t) tw	0.058917	*
t Critical tv	2.200985	

At maximum rise in back skin temperature:

330 vs 770			330 vs 770+			330 vs 950		
t-Test: Paired Two Sample for Means			t-Test: Paired Two Sample for Means			t-Test: Paired Two Sample for Means		
	Variable 1	Variable 2		Variable 1	Variable 2		Variable 1	Variable 2
Mean	7.025	6.40875	Mean	7.025	6.40875	Mean	7.025	6.83
Variance	2.97	0.587355	Variance	2.97	0.587355	Variance	2.97	1.0128
Observatic	8	8	Observatic	8	8	Observatic	8	8
Pearson Cc	0.241444		Pearson Cc	0.241444		Pearson Cc	0.371804	
Hypothesi:	0		Hypothesi:	0		Hypothesi:	0	
df	7		df	7		df	7	
t Stat	1.020099		t Stat	1.020099		t Stat	0.336087	
P(T<=t) on	0.170818		P(T<=t) on	0.170818		P(T<=t) on	0.373327	
t Critical o	1.894579		t Critical o	1.894579		t Critical o	1.894579	
P(T<=t) tw	0.341636	nsd	P(T<=t) tw	0.341636	nsd	P(T<=t) tw	0.746654	nsd
t Critical tv	2.364624		t Critical tv	2.364624		t Critical tv	2.364624	
330 vs double			770 vs 770+			770 vs 950		
t-Test: Two-Sample Assuming Unequal Vari			t-Test: Paired Two Sample for Means			t-Test: Paired Two Sample for Means		
	Variable 1	Variable 2		Variable 1	Variable 2		Variable 1	Variable 2
Mean	7.025	6.238571	Mean	6.40875	6.19625	Mean	6.40875	6.83
Variance	2.97	1.080081	Variance	0.587355	1.026855	Variance	0.587355	1.0128
Observatic	8	7	Observatic	8	8	Observatic	8	8
Hypothesi:	0		Pearson Cc	0.267657		Pearson Cc	0.626787	
df	12		Hypothesi:	0		Hypothesi:	0	
t Stat	1.084809		df	7		df	7	
P(T<=t) on	0.14966		t Stat	0.549021		t Stat	-1.4972	
t Critical o	1.782288		P(T<=t) on	0.300029		P(T<=t) on	0.089003	
P(T<=t) tw	0.29932	nsd	t Critical o	1.894579		t Critical o	1.894579	
t Critical tv	2.178813		P(T<=t) tw	0.600058	nsd	P(T<=t) tw	0.178006	nsd
			t Critical tv	2.364624		t Critical tv	2.364624	

770 vs double

t-Test: Two-Sample Assuming Unequal Varia

	Variable 1	Variable 2
Mean	6.40875	6.238571
Variance	0.587355	1.080081
Observatic	8	7
Hypothesi:	0	
df	11	
t Stat	0.356621	
P(T<=t) on	0.364061	
t Critical o	1.795885	
P(T<=t) tw	0.728122	nsd
t Critical tv	2.200985	

770+ vs 950

t-Test: Paired Two Sample for Means

	Variable 1	Variable 2
Mean	6.19625	6.83
Variance	1.026855	1.0128
Observatic	8	8
Pearson C(	0.657648	
Hypothesi:	0	
df	7	
t Stat	-2.14505	
P(T<=t) on	0.034558	
t Critical o	1.894579	
P(T<=t) tw	0.069117	*
t Critical tv	2.364624	

770+ vs double

t-Test: Two-Sample Assuming Unequal Varia

	Variable 1	Variable 2
Mean	6.19625	6.238571
Variance	1.026855	1.080081
Observatic	8	7
Hypothesi:	0	
df	13	
t Stat	-0.0796	
P(T<=t) on	0.468882	
t Critical o	1.770933	
P(T<=t) tw	0.937765	nsd
t Critical tv	2.160369	

950 vs double

t-Test: Two-Sample Assuming Unequal Variances

	Variable 1	Variable 2
Mean	6.83	6.238571
Variance	1.0128	1.080081
Observatic	8	7
Hypothesi:	0	
df	13	
t Stat	1.115908	
P(T<=t) on	0.142332	
t Critical o	1.770933	
P(T<=t) tw	0.284664	nsd
t Critical tv	2.160369	

Forearm Skin Temperature:

At 120 min:

330 vs 770

t-Test: Paired Two Sample for Means

	Variable 1	*Variable 2*
Mean	3.4675	3.5925
Variance	1.742679	0.713821
Observatio	8	8
Pearson Co	0.818406	
Hypothesiz	0	
df	7	
t Stat	-0.44511	
P(T<=t) on	0.334839	
t Critical o	1.894579	
P(T<=t) tw	0.669677	nsd
t Critical tv	2.364624	

330 vs 770+

t-Test: Paired Two Sample for Means

	Variable 1	*Variable 2*
Mean	3.4675	3.32875
Variance	1.742679	2.81287
Observatio	8	8
Pearson Co	0.851832	
Hypothesiz	0	
df	7	
t Stat	0.443338	
P(T<=t) on	0.33545	
t Critical o	1.894579	
P(T<=t) tw	0.6709	nsd
t Critical tv	2.364624	

330 vs 950

t-Test: Paired Two Sample for Means

	Variable 1	*Variable 2*
Mean	3.4675	4.05625
Variance	1.742679	0.93317
Observatio	8	8
Pearson Co	0.645354	
Hypothesiz	0	
df	7	
t Stat	-1.64089	
P(T<=t) on	0.072413	
t Critical o	1.894579	
P(T<=t) tw	0.144826	nsd
t Critical tv	2.364624	

330 vs double

t-Test: Paired Two Sample for Means

	Variable 1	*Variable 2*
Mean	3.4675	3.29125
Variance	1.742679	2.631927
Observatio	8	8
Pearson Co	0.843749	
Hypothesiz	0	
df	7	
t Stat	0.571606	
P(T<=t) on	0.292734	
t Critical o	1.894579	
P(T<=t) tw	0.585467	nsd
t Critical tv	2.364624	

770 vs 770+

t-Test: Paired Two Sample for Means

	Variable 1	*Variable 2*
Mean	3.5925	3.32875
Variance	0.713821	2.81287
Observatio	8	8
Pearson Co	0.720912	
Hypothesiz	0	
df	7	
t Stat	0.612456	
P(T<=t) on	0.279799	
t Critical o	1.894579	
P(T<=t) tw	0.559598	nsd
t Critical tv	2.364624	

770 vs 950

t-Test: Paired Two Sample for Means

	Variable 1	*Variable 2*
Mean	3.5925	4.05625
Variance	0.713821	0.93317
Observatio	8	8
Pearson Co	0.773601	
Hypothesiz	0	
df	7	
t Stat	-2.11609	
P(T<=t) on	0.036068	
t Critical o	1.894579	
P(T<=t) tw	0.072136	*
t Critical tv	2.364624	

770 vs double

t-Test: Paired Two Sample for Means

	Variable 1	*Variable 2*
Mean	3.5925	3.29125
Variance	0.713821	2.631927
Observatio	8	8
Pearson Co	0.585896	
Hypothesiz	0	
df	7	
t Stat	0.64602	
P(T<=t) on	0.26943	
t Critical o	1.894579	
P(T<=t) tw	0.53886	nsd
t Critical tv	2.364624	

770+ vs 950

t-Test: Paired Two Sample for Means

	Variable 1	*Variable 2*
Mean	3.32875	4.05625
Variance	2.81287	0.93317
Observatio	8	8
Pearson Co	0.348227	
Hypothesiz	0	
df	7	
t Stat	-1.2718	
P(T<=t) on	0.122032	
t Critical o	1.894579	
P(T<=t) tw	0.244064	nsd
t Critical tv	2.364624	

770+ vs double

t-Test: Paired Two Sample for Means

	Variable 1	*Variable 2*
Mean	3.32875	3.29125
Variance	2.81287	2.631927
Observatio	8	8
Pearson Co	0.868896	
Hypothesiz	0	
df	7	
t Stat	0.125309	
P(T<=t) on	0.451901	
t Critical o	1.894579	
P(T<=t) tw	0.903802	nsd
t Critical tv	2.364624	

950 vs double		
t-Test: Paired Two Sample for Means		
	Variable 1	Variable 2
Mean	4.05625	3.29125
Variance	0.93317	2.631927
Observatic	8	8
Pearson C(	0.516128	
Hypothesi:	0	
df	7	
t Stat	1.550537	
P(T<=t) on	0.082474	
t Critical o	1.894579	
P(T<=t) tw	0.164948	nsd
t Critical tv	2.364624	

At maximum rise in forearm skin temperature:

330 vs 770			330 vs 770+			330 vs 950		
t-Test: Paired Two Sample for Means			t-Test: Paired Two Sample for Means			t-Test: Paired Two Sample for Means		
	Variable 1	Variable 2		Variable 1	Variable 2		Variable 1	Variable 2
Mean	3.7325	3.7475	Mean	3.7325	3.715	Mean	3.7325	4.19375
Variance	1.192221	0.646964	Variance	1.192221	1.502914	Variance	1.192221	0.622855
Observatic	8	8	Observatic	8	8	Observatic	8	8
Pearson C(	0.7306		Pearson C(	0.947067		Pearson C(	0.499497	
Hypothesi:	0		Hypothesi:	0		Hypothesi:	0	
df	7		df	7		df	7	
t Stat	-0.0569		t Stat	0.123868		t Stat	-1.33555	
P(T<=t) on	0.478106		P(T<=t) on	0.452451		P(T<=t) on	0.111744	
t Critical o	1.894579		t Critical o	1.894579		t Critical o	1.894579	
P(T<=t) tw	0.956212	nsd	P(T<=t) tw	0.904901	nsd	P(T<=t) tw	0.223487	nsd
t Critical tv	2.364624		t Critical tv	2.364624		t Critical tv	2.364624	
330 vs double			770 vs 770+			770 vs 950		
t-Test: Paired Two Sample for Means			t-Test: Paired Two Sample for Means			t-Test: Paired Two Sample for Means		
	Variable 1	Variable 2		Variable 1	Variable 2		Variable 1	Variable 2
Mean	3.7325	3.73	Mean	3.7475	3.715	Mean	3.7475	4.19375
Variance	1.192221	1.813629	Variance	0.646964	1.502914	Variance	0.646964	0.622855
Observatic	8	8	Observatic	8	8	Observatic	8	8
Pearson C(	0.892851		Pearson C(	0.543181		Pearson C(	0.749707	
Hypothesi:	0		Hypothesi:	0		Hypothesi:	0	
df	7		df	7		df	7	
t Stat	0.01147		t Stat	0.088509		t Stat	-2.23826	
P(T<=t) on	0.495584		P(T<=t) on	0.465976		P(T<=t) on	0.030116	
t Critical o	1.894579		t Critical o	1.894579		t Critical o	1.894579	
P(T<=t) tw	0.991168	nsd	P(T<=t) tw	0.931951	nsd	P(T<=t) tw	0.060232	*
t Critical tv	2.364624		t Critical tv	2.364624		t Critical tv	2.364624	

770 vs double

t-Test: Paired Two Sample for Means

	Variable 1	Variable 2	
Mean	3.7475	3.73	
Variance	0.646964	1.813629	
Observatic	8	8	
Pearson C(	0.689403		
Hypothesiz	0		
df	7		
t Stat	0.050334		
P(T<=t) on	0.480631		
t Critical o	1.894579		
P(T<=t) tw	0.961263	nsd	
t Critical tv	2.364624		

770+ vs 950

t-Test: Paired Two Sample for Means

	Variable 1	Variable 2	
Mean	3.715	4.19375	
Variance	1.502914	0.622855	
Observatic	8	8	
Pearson C(	0.250456		
Hypothesiz	0		
df	7		
t Stat	-1.05702		
P(T<=t) on	0.162806		
t Critical o	1.894579		
P(T<=t) tw	0.325611	nsd	
t Critical tv	2.364624		

770+ vs double

t-Test: Paired Two Sample for Means

	Variable 1	Variable 2	
Mean	3.715	3.73	
Variance	1.502914	1.813629	
Observatic	8	8	
Pearson C(	0.79507		
Hypothesiz	0		
df	7		
t Stat	-0.05103		
P(T<=t) on	0.480364		
t Critical o	1.894579		
P(T<=t) tw	0.960728	nsd	
t Critical tv	2.364624		

950 vs double

t-Test: Paired Two Sample for Means

	Variable 1	Variable 2	
Mean	4.19375	3.73	
Variance	0.622855	1.813629	
Observatic	8	8	
Pearson C(	0.725415		
Hypothesiz	0		
df	7		
t Stat	1.386892		
P(T<=t) on	0.104016		
t Critical o	1.894579		
P(T<=t) tw	0.208032	nsd	
t Critical tv	2.364624		

Thigh Skin Temperature:

At maximum change in thigh skin temperature:

330 vs 770

t-Test: Paired Two Sample for Means

	Variable 1	*Variable 2*	
Mean	6.45625	6.1475	
Variance	1.206598	0.567164	
Observatic	8	8	
Pearson C	0.654308		
Hypothesi	0		
df	7		
t Stat	1.050379		
P(T<=t) on	0.164224		
t Critical o	1.894579		
P(T<=t) tw	0.328448	nsd	
t Critical tv	2.364624		

330 vs 770+

t-Test: Paired Two Sample for Means

	Variable 1	*Variable 2*	
Mean	6.45625	5.995	
Variance	1.206598	0.511657	
Observatic	8	8	
Pearson C	0.616709		
Hypothesi	0		
df	7		
t Stat	1.507314		
P(T<=t) on	0.08773		
t Critical o	1.894579		
P(T<=t) tw	0.17546	nsd	
t Critical tv	2.364624		

330 vs 950

t-Test: Paired Two Sample for Means

	Variable 1	*Variable 2*	
Mean	6.45625	6.30875	
Variance	1.206598	0.596012	
Observatic	8	8	
Pearson C	0.538825		
Hypothesi	0		
df	7		
t Stat	0.442538		
P(T<=t) on	0.335726		
t Critical o	1.894579		
P(T<=t) tw	0.671451	nsd	
t Critical tv	2.364624		

330 vs double

t-Test: Two-Sample Assuming Unequal Varia

	Variable 1	*Variable 2*	
Mean	6.45625	6.198571	
Variance	1.206598	1.308281	
Observatic	8	7	
Hypothesi	0		
df	13		
t Stat	0.443403		
P(T<=t) on	0.332382		
t Critical o	1.770933		
P(T<=t) tw	0.664764		
t Critical tv	2.160369	nsd	

770 vs 770+

t-Test: Paired Two Sample for Means

	Variable 1	*Variable 2*	
Mean	6.1475	5.995	
Variance	0.567164	0.511657	
Observatic	8	8	
Pearson C	0.257553		
Hypothesi	0		
df	7		
t Stat	0.481845		
P(T<=t) on	0.322308		
t Critical o	1.894579		
P(T<=t) tw	0.644616	nsd	
t Critical tv	2.364624		

770 vs 950

t-Test: Paired Two Sample for Means

	Variable 1	*Variable 2*	
Mean	6.1475	6.30875	
Variance	0.567164	0.596012	
Observatic	8	8	
Pearson C	0.868376		
Hypothesi	0		
df	7		
t Stat	-1.16443		
P(T<=t) on	0.141197		
t Critical o	1.894579		
P(T<=t) tw	0.282394	nsd	
t Critical tv	2.364624		

770 vs double

t-Test: Two-Sample Assuming Unequal Varia

	Variable 1	*Variable 2*	
Mean	6.1475	6.198571	
Variance	0.567164	1.308281	
Observatic	8	7	
Hypothesi	0		
df	10		
t Stat	-0.10059		
P(T<=t) on	0.460933		
t Critical o	1.812461		
P(T<=t) tw	0.921866		
t Critical tv	2.228139	nsd	

770+ vs 950

t-Test: Paired Two Sample for Means

	Variable 1	*Variable 2*	
Mean	5.995	6.30875	
Variance	0.511657	0.596012	
Observatic	8	8	
Pearson C	0.292853		
Hypothesi	0		
df	7		
t Stat	-1.00209		
P(T<=t) on	0.174837		
t Critical o	1.894579		
P(T<=t) tw	0.349673	nsd	
t Critical tv	2.364624		

770+ vs double

t-Test: Two-Sample Assuming Unequal Varia

	Variable 1	*Variable 2*	
Mean	5.995	6.198571	
Variance	0.511657	1.308281	
Observatic	8	7	
Hypothesi	0		
df	10		
t Stat	-0.40645		
P(T<=t) on	0.346487		
t Critical o	1.812461		
P(T<=t) tw	0.692975		
t Critical tv	2.228139	nsd	

950 vs double				
t-Test: Two-Sample Assuming Unequal Variances				
	Variable 1	*Variable 2*		
Mean	6.30875	6.198571		
Variance	0.596012	1.308281		
Observatic	8	7		
Hypothesi:	0			
df	10			
t Stat	0.215499			
P(T<=t) on	0.416855			
t Critical o	1.812461			
P(T<=t) tw	0.83371			
t Critical tv	2.228139	nsd		

Overall Skin Temperature:

At 120 min:

330 vs 770		
t-Test: Paired Two Sample for Means		
	Variable 1	*Variable 2*
Mean	4.699688	4.509688
Variance	2.234879	0.864356
Observatio	8	8
Pearson Co	0.733275	
Hypothesiz	0	
df	7	
t Stat	0.521743	
P(T<=t) on	0.308973	
t Critical o	1.894579	
P(T<=t) tw	0.617946	nsd
t Critical tv	2.364624	

330 vs 770+		
t-Test: Paired Two Sample for Means		
	Variable 1	*Variable 2*
Mean	4.699688	4.110313
Variance	2.234879	1.127145
Observatio	8	8
Pearson Co	0.87776	
Hypothesiz	0	
df	7	
t Stat	2.196935	
P(T<=t) on	0.03201	
t Critical o	1.894579	
P(T<=t) tw	0.06402	*
t Critical tv	2.364624	

330 vs 950		
t-Test: Paired Two Sample for Means		
	Variable 1	*Variable 2*
Mean	4.699688	4.83125
Variance	2.234879	1.207177
Observatio	8	8
Pearson Co	0.704184	
Hypothesiz	0	
df	7	
t Stat	-0.35025	
P(T<=t) on	0.368228	
t Critical o	1.894579	
P(T<=t) tw	0.736456	nsd
t Critical tv	2.364624	

330 vs double		
t-Test: Paired Two Sample for Means		
	Variable 1	*Variable 2*
Mean	4.699688	4.589844
Variance	2.234879	3.146609
Observatio	8	8
Pearson Co	0.623879	
Hypothesiz	0	
df	7	
t Stat	0.215804	
P(T<=t) on	0.417647	
t Critical o	1.894579	
P(T<=t) tw	0.835294	nsd
t Critical tv	2.364624	

770 vs 770+		
t-Test: Paired Two Sample for Means		
	Variable 1	*Variable 2*
Mean	4.509688	4.110313
Variance	0.864356	1.127145
Observatio	8	8
Pearson Co	0.705769	
Hypothesiz	0	
df	7	
t Stat	1.460441	
P(T<=t) on	0.093774	
t Critical o	1.894579	
P(T<=t) tw	0.187548	nsd
t Critical tv	2.364624	

770 vs 950		
t-Test: Paired Two Sample for Means		
	Variable 1	*Variable 2*
Mean	4.509688	4.83125
Variance	0.864356	1.207177
Observatio	8	8
Pearson Co	0.880683	
Hypothesiz	0	
df	7	
t Stat	-1.74288	
P(T<=t) on	0.062442	
t Critical o	1.894579	
P(T<=t) tw	0.124884	nsd
t Critical tv	2.364624	

770 vs double		
t-Test: Paired Two Sample for Means		
	Variable 1	*Variable 2*
Mean	4.509688	4.589844
Variance	0.864356	3.146609
Observatio	8	8
Pearson Co	0.622508	
Hypothesiz	0	
df	7	
t Stat	-0.16203	
P(T<=t) on	0.437928	
t Critical o	1.894579	
P(T<=t) tw	0.875856	nsd
t Critical tv	2.364624	

770+ vs 950		
t-Test: Paired Two Sample for Means		
	Variable 1	*Variable 2*
Mean	4.110313	4.83125
Variance	1.127145	1.207177
Observatio	8	8
Pearson Co	0.7604	
Hypothesiz	0	
df	7	
t Stat	-2.72404	
P(T<=t) on	0.014796	
t Critical o	1.894579	
P(T<=t) tw	0.029592	**
t Critical tv	2.364624	

770+ vs double		
t-Test: Paired Two Sample for Means		
	Variable 1	*Variable 2*
Mean	4.110313	4.589844
Variance	1.127145	3.146609
Observatio	8	8
Pearson Co	0.826067	
Hypothesiz	0	
df	7	
t Stat	-1.25804	
P(T<=t) on	0.124358	
t Critical o	1.894579	
P(T<=t) tw	0.248716	nsd
t Critical tv	2.364624	

950 vs double		
t-Test: Paired Two Sample for Means		
	Variable 1	*Variable 2*
Mean	4.83125	4.589844
Variance	1.207177	3.146609
Observatic	8	8
Pearson Cc	0.763566	
Hypothesiz	0	
df	7	
t Stat	0.581778	
P(T<=t) on	0.289481	
t Critical o	1.894579	
P(T<=t) tw	0.578962	nsd
t Critical tv	2.364624	

At maximum rise in overall skin temperature:

330 vs 770		
t-Test: Paired Two Sample for Means		
	Variable 1	*Variable 2*
Mean	5.135	4.960625
Variance	1.2411	0.487566
Observatic	8	8
Pearson Cc	0.386863	
Hypothesiz	0	
df	7	
t Stat	0.464631	
P(T<=t) on	0.328151	
t Critical o	1.894579	
P(T<=t) tw	0.656302	nsd
t Critical tv	2.364624	

330 vs 770+		
t-Test: Paired Two Sample for Means		
	Variable 1	*Variable 2*
Mean	5.135	4.775625
Variance	1.2411	0.634805
Observatic	8	8
Pearson Cc	0.848624	
Hypothesiz	0	
df	7	
t Stat	1.672401	
P(T<=t) on	0.069182	
t Critical o	1.894579	
P(T<=t) tw	0.138364	nsd
t Critical tv	2.364624	

330 vs 950		
t-Test: Paired Two Sample for Means		
	Variable 1	*Variable 2*
Mean	5.135	5.172188
Variance	1.2411	0.796935
Observatic	8	8
Pearson Cc	0.374676	
Hypothesiz	0	
df	7	
t Stat	-0.09251	
P(T<=t) on	0.464443	
t Critical o	1.894579	
P(T<=t) tw	0.928886	nsd
t Critical tv	2.364624	

330 vs double		
t-Test: Two-Sample Assuming Unequal Varia		
	Variable 1	*Variable 2*
Mean	5.135	4.850714
Variance	1.2411	0.900149
Observatic	8	7
Hypothesiz	0	
df	13	
t Stat	0.533706	
P(T<=t) on	0.301276	
t Critical o	1.770933	
P(T<=t) tw	0.602551	
t Critical tv	2.160369	nsd

770 vs 770+		
t-Test: Paired Two Sample for Means		
	Variable 1	*Variable 2*
Mean	4.960625	4.775625
Variance	0.487566	0.634805
Observatic	8	8
Pearson Cc	0.337543	
Hypothesiz	0	
df	7	
t Stat	0.605502	
P(T<=t) on	0.281977	
t Critical o	1.894579	
P(T<=t) tw	0.563953	nsd
t Critical tv	2.364624	

770 vs 950		
t-Test: Paired Two Sample for Means		
	Variable 1	*Variable 2*
Mean	4.960625	5.172188
Variance	0.487566	0.796935
Observatic	8	8
Pearson Cc	0.827544	
Hypothesiz	0	
df	7	
t Stat	-1.19011	
P(T<=t) on	0.136398	
t Critical o	1.894579	
P(T<=t) tw	0.272797	nsd
t Critical tv	2.364624	

770 vs double

t-Test: Two-Sample Assuming Unequal Vari

	Variable 1	*Variable 2*
Mean	4.960625	4.850714
Variance	0.487566	0.900149
Observatic	8	7
Hypothesi:	0	
df	11	
t Stat	0.252459	
P(T<=t) on	0.402671	
t Critical o	1.795885	
P(T<=t) tw	0.805341	nsd
t Critical tv	2.200985	

770+ vs 950

t-Test: Paired Two Sample for Means

	Variable 1	*Variable 2*
Mean	4.775625	5.172188
Variance	0.634805	0.796935
Observatic	8	8
Pearson C	0.513758	
Hypothesi:	0	
df	7	
t Stat	-1.33976	
P(T<=t) on	0.111091	
t Critical o	1.894579	
P(T<=t) tw	0.222181	nsd
t Critical tv	2.364624	

770+ vs double

t-Test: Two-Sample Assuming Unequal Varia

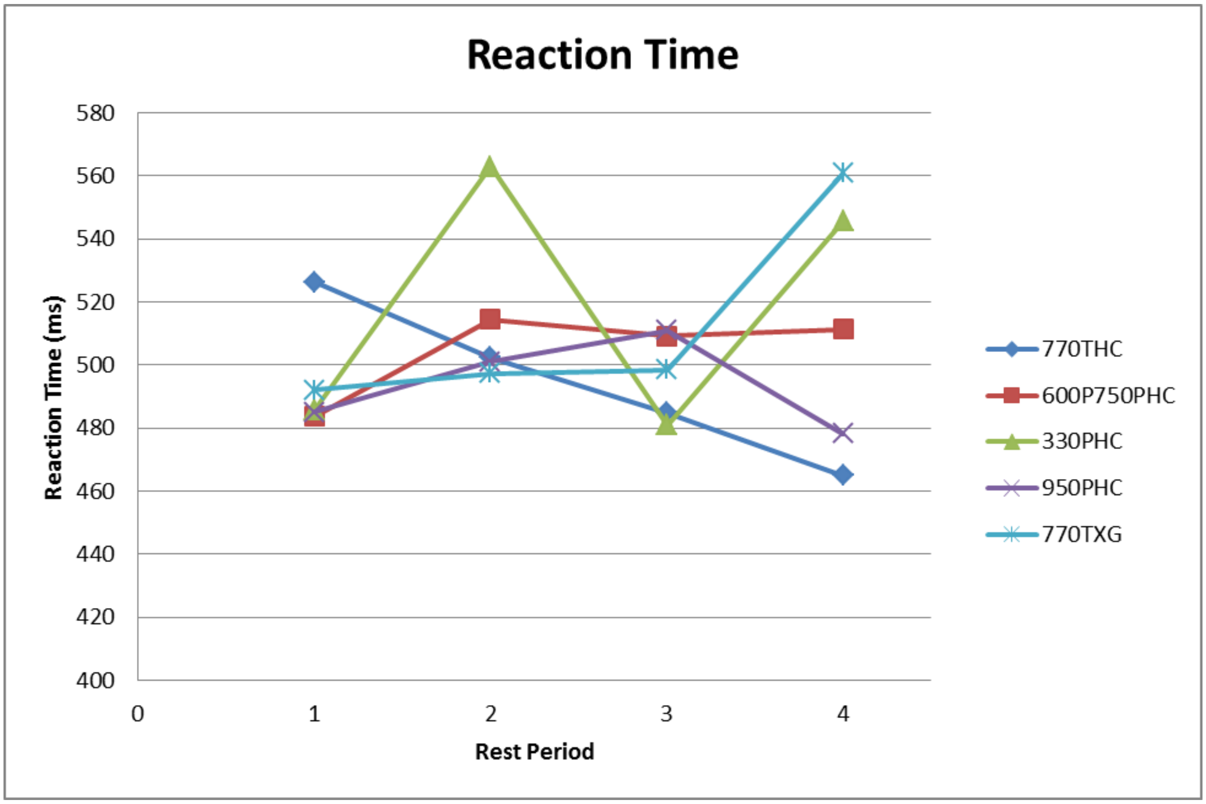
	Variable 1	*Variable 2*
Mean	4.775625	4.850714
Variance	0.634805	0.900149
Observatic	8	7
Hypothesi:	0	
df	12	
t Stat	-0.16467	
P(T<=t) on	0.435974	
t Critical o	1.782288	
P(T<=t) tw	0.871948	
t Critical tv	2.178813	nsd

950 vs double

t-Test: Two-Sample Assuming Unequal Variances

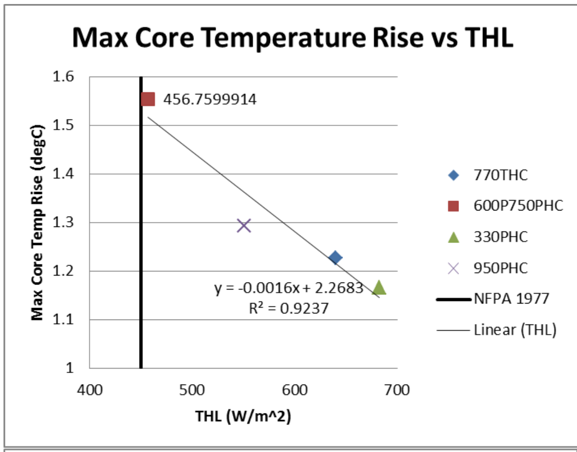
	Variable 1	*Variable 2*
Mean	5.172188	4.850714
Variance	0.796935	0.900149
Observatic	8	7
Hypothesi:	0	
df	12	
t Stat	0.672942	
P(T<=t) on	0.256868	
t Critical o	1.782288	
P(T<=t) tw	0.513735	
t Critical tv	2.178813	nsd

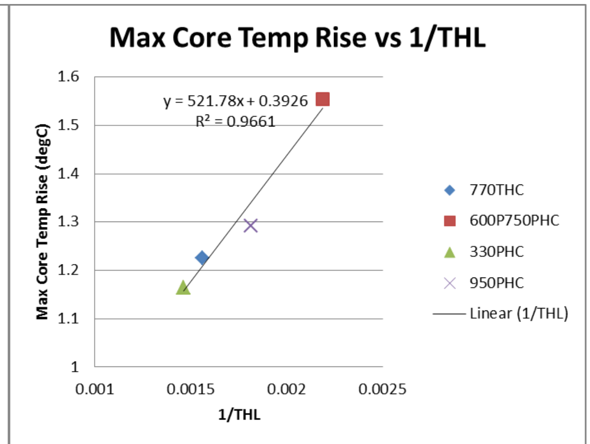
Appendix G: Reaction Time Data

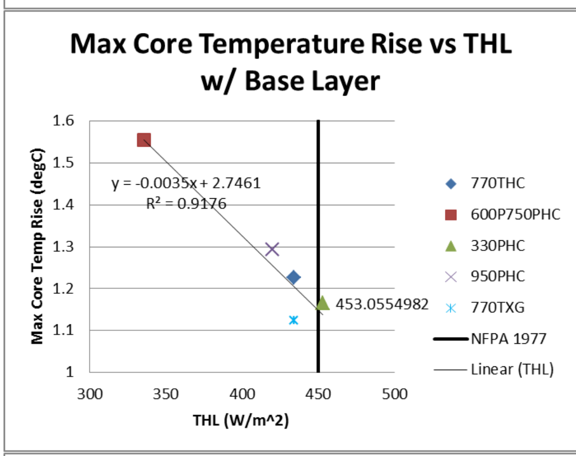


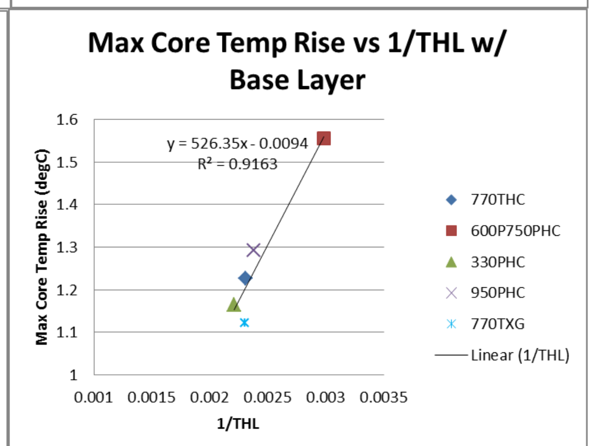
Appendix H: Wear Trial and Instrumentation Correlations

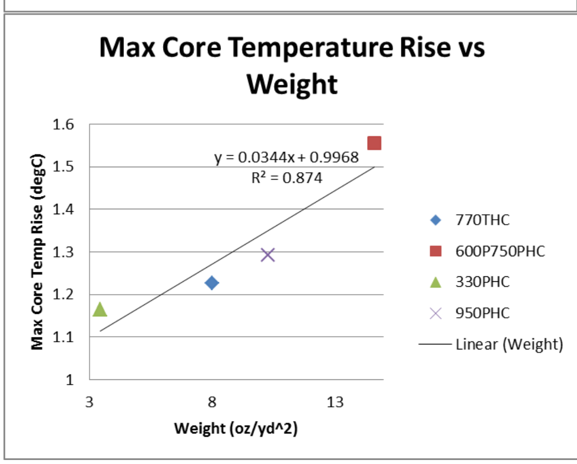
Max Core Temperature Rise Correlations:

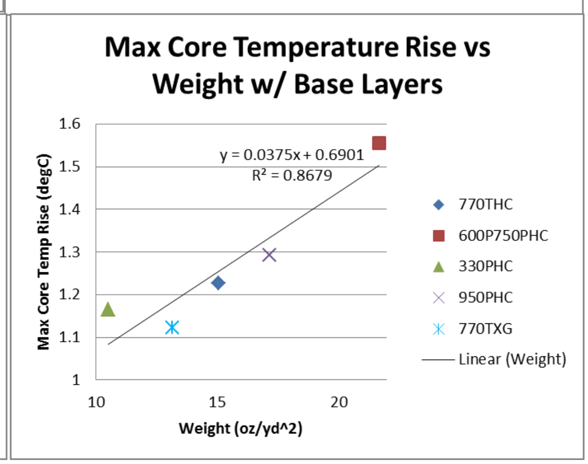


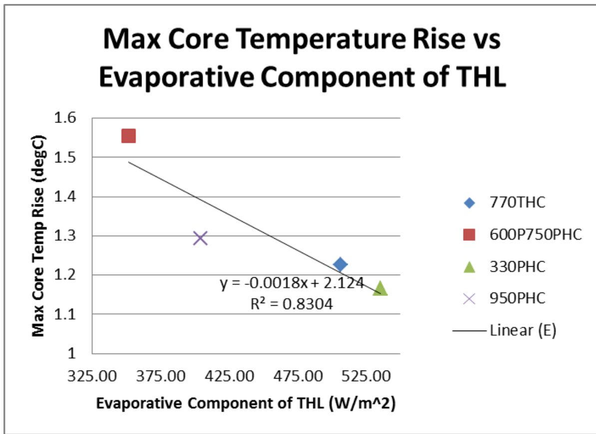


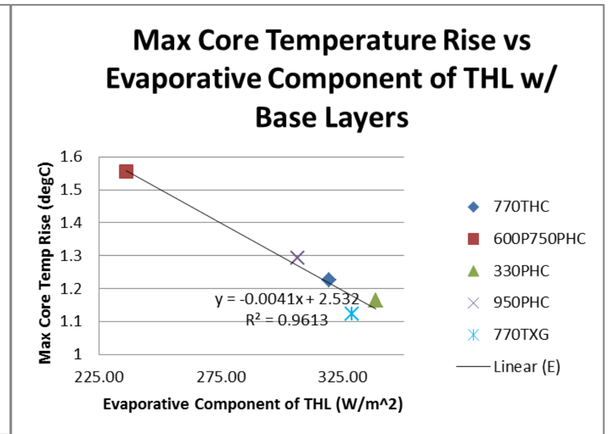


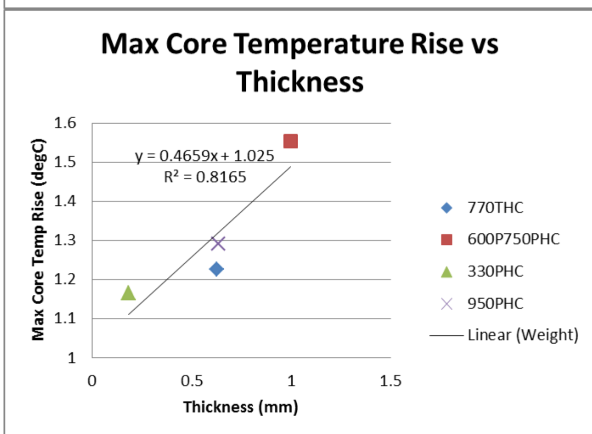


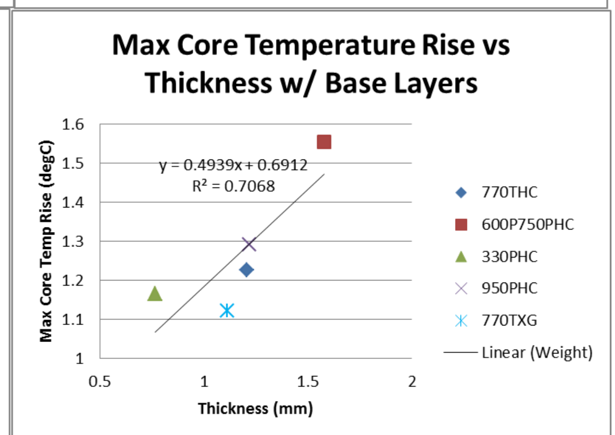


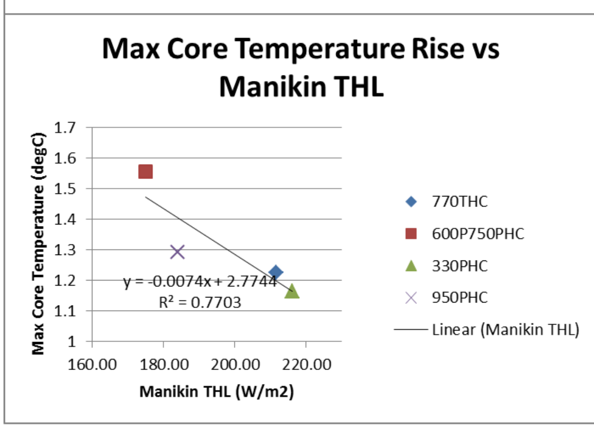


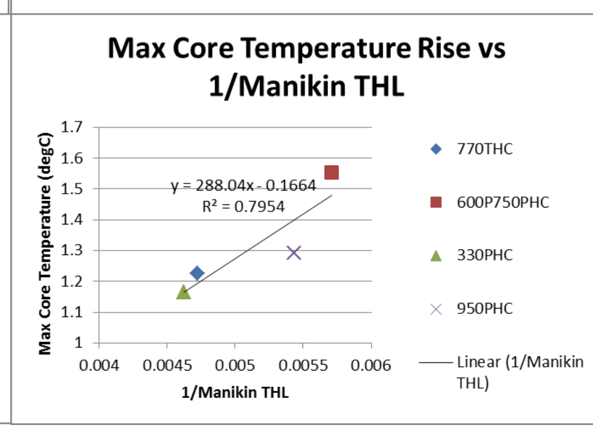

Max Core Temperature Rise vs Evaporative Component of THL
Max Core Temp Rise (degC)
Evaporative Component of THL (W/m^2)
y = -0.0018x + 2.124
R² = 0.8304
770THC
600P750PHC
330PHC
950PHC
Linear (E)

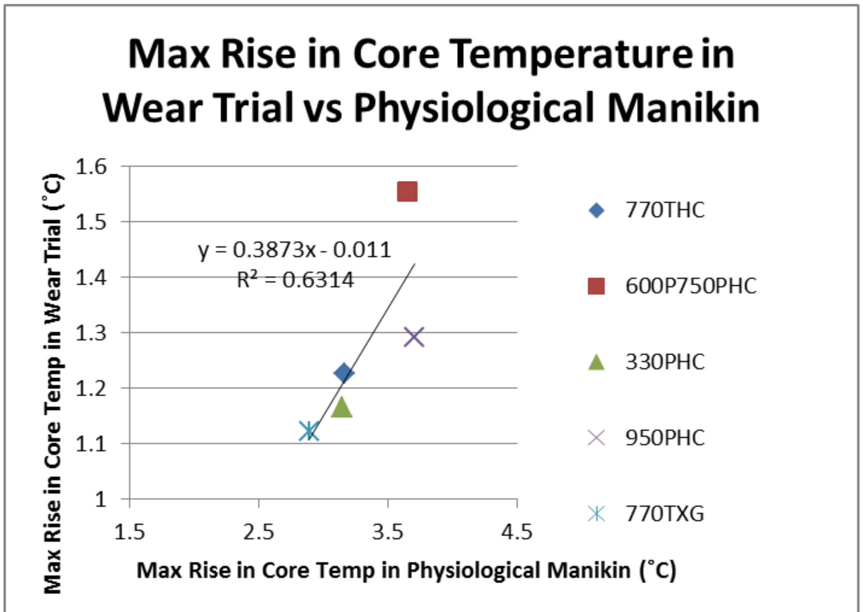

Max Core Temperature Rise vs Evaporative Component of THL w/ Base Layers
Max Core Temp Rise (degC)
Evaporative Component of THL (W/m^2)
y = -0.0041x + 2.532
R² = 0.9613
770THC
600P750PHC
330PHC
950PHC
770TXG
Linear (E)


Max Core Temperature Rise vs Thickness
Max Core Temp Rise (degC)
Thickness (mm)
y = 0.4659x + 1.025
R² = 0.8165
770THC
600P750PHC
330PHC
950PHC
Linear (Weight)

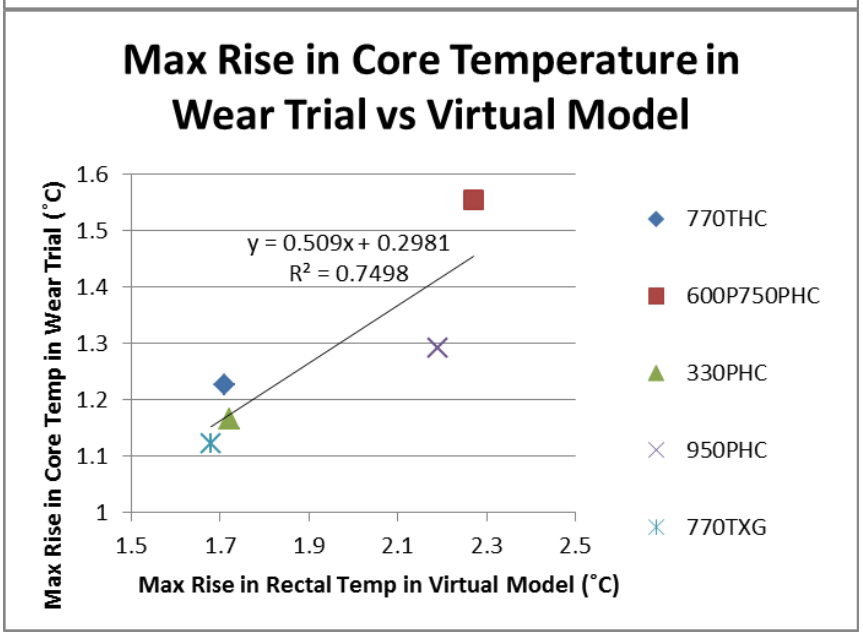

Max Core Temperature Rise vs Thickness w/ Base Layers
Max Core Temp Rise (degC)
Thickness (mm)
y = 0.4939x + 0.6912
R² = 0.7068
770THC
600P750PHC
330PHC
950PHC
770TXG
Linear (Weight)


Max Core Temperature Rise vs Manikin THL
Max Core Temperature (degC)
Manikin THL (W/m2)
y = -0.0074x + 2.7744
R² = 0.7703
770THC
600P750PHC
330PHC
950PHC
Linear (Manikin THL)


Max Core Temperature Rise vs 1/Manikin THL
Max Core Temperature (degC)
1/Manikin THL
y = 288.04x - 0.1664
R² = 0.7954
770THC
600P750PHC
330PHC
950PHC
Linear (1/Manikin THL)

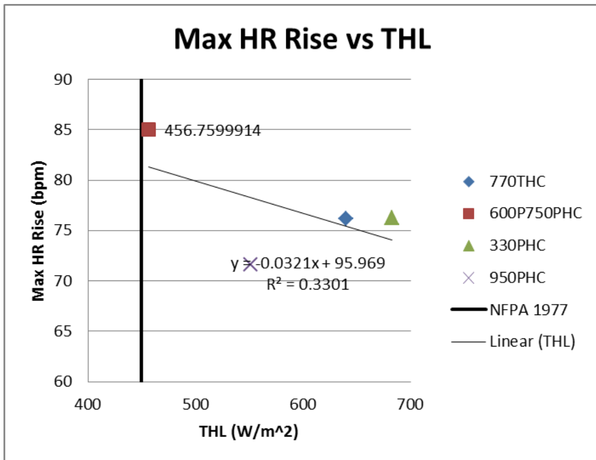


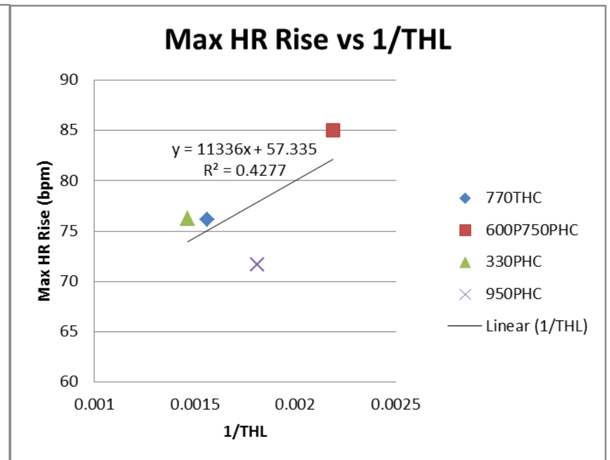
Max Rise in Core Temperature in Wear Trial vs Physiological Manikin
y = 0.3873x - 0.011
R² = 0.6314
Max Rise in Core Temp in Wear Trial (˚C)
Max Rise in Core Temp in Physiological Manikin (˚C)
1.6
1.5
1.4
1.3
1.2
1.1
1
1.5
2.5
3.5
4.5
770THC
600P750PHC
330PHC
950PHC
770TXG

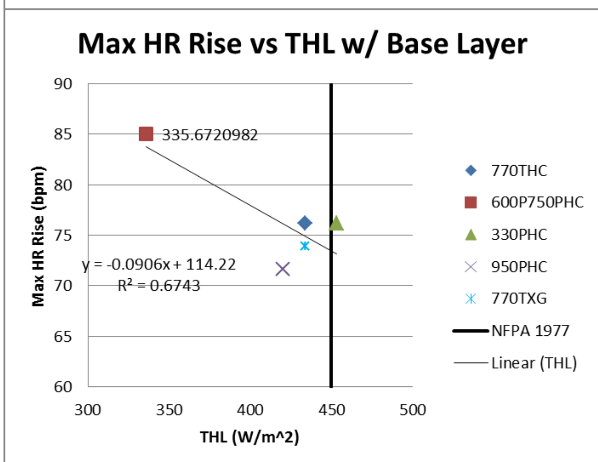


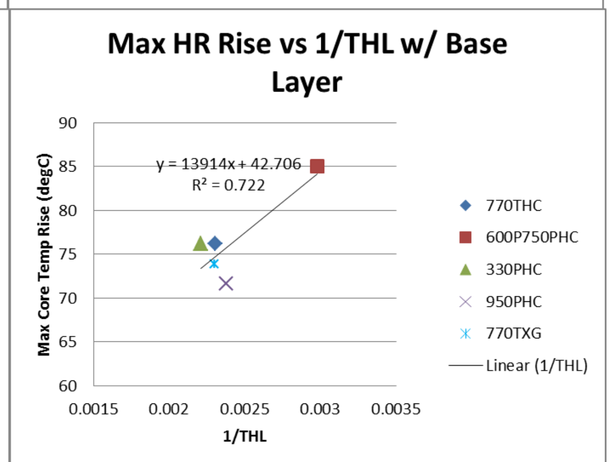
Max Rise in Core Temperature in Wear Trial vs Virtual Model
y = 0.509x + 0.2981
R² = 0.7498
Max Rise in Core Temp in Wear Trial (˚C)
Max Rise in Rectal Temp in Virtual Model (˚C)
1.6
1.5
1.4
1.3
1.2
1.1
1
1.5
1.7
1.9
2.1
2.3
2.5
770THC
600P750PHC
330PHC
950PHC
770TXG

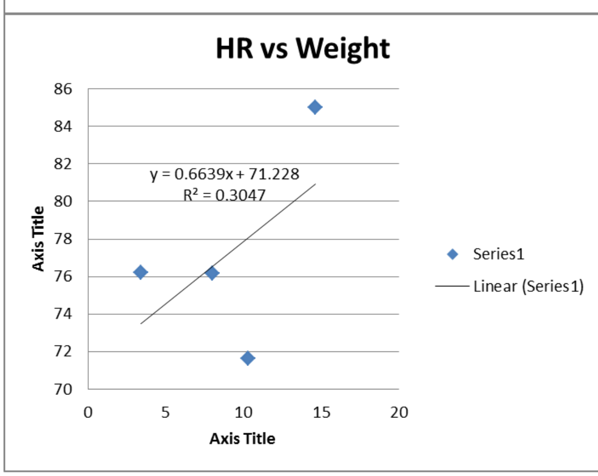
Maximum Rise in Heart Rate Correlations:

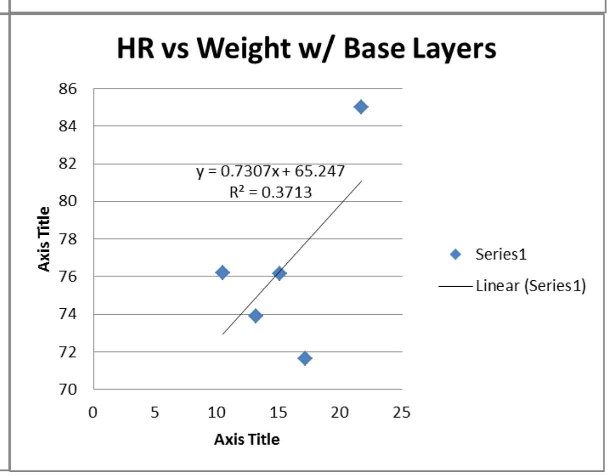


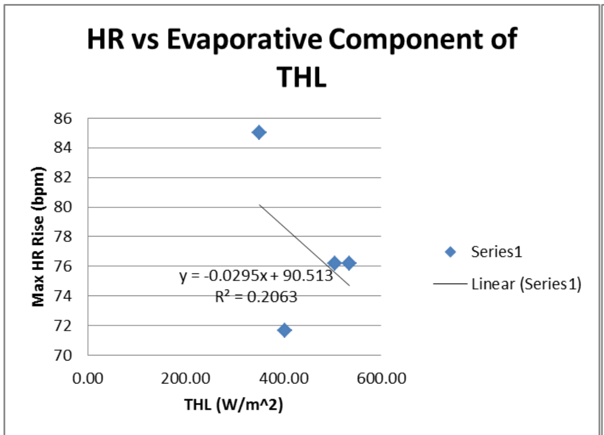




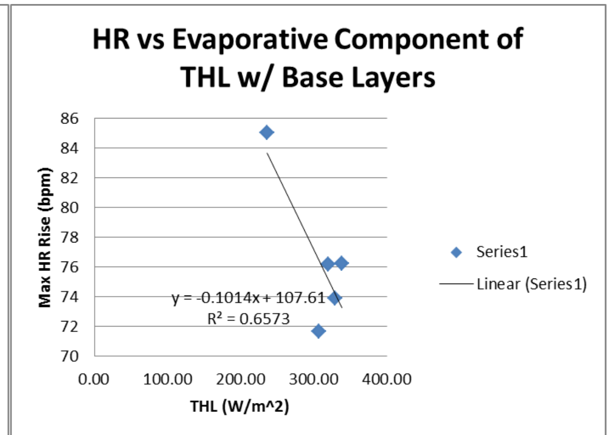




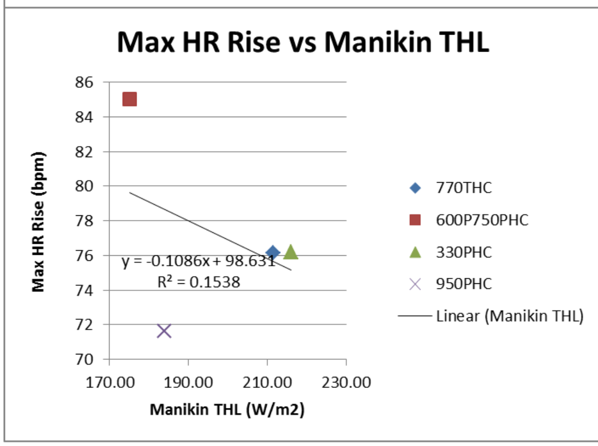




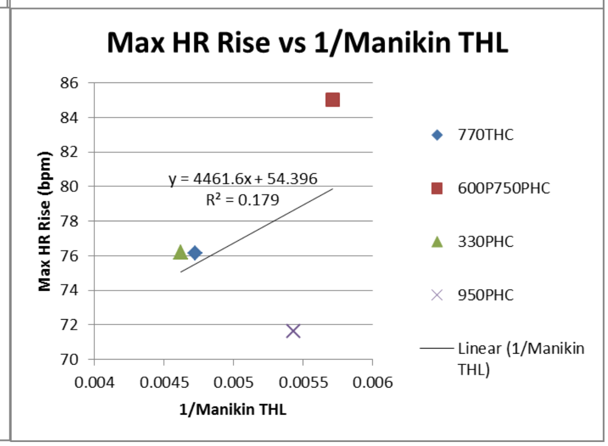
HR vs Evaporative Component of THL
Max HR Rise (bpm)
THL (W/m^2)
y = -0.0295x + 90.513
R² = 0.2063
Series1
Linear (Series1)



HR vs Evaporative Component of THL w/ Base Layers
Max HR Rise (bpm)
THL (W/m^2)
y = -0.1014x + 107.61
R² = 0.6573
Series1
Linear (Series1)

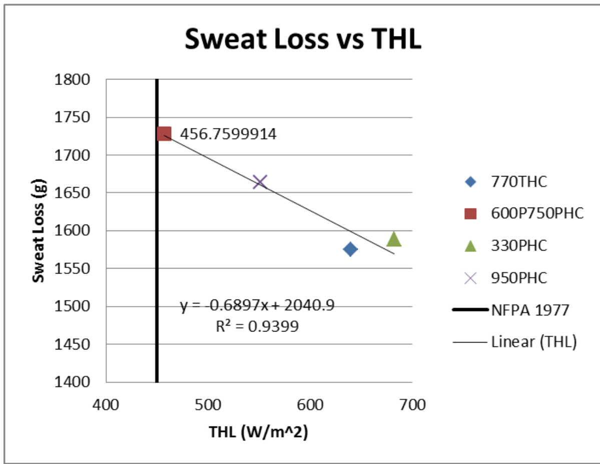


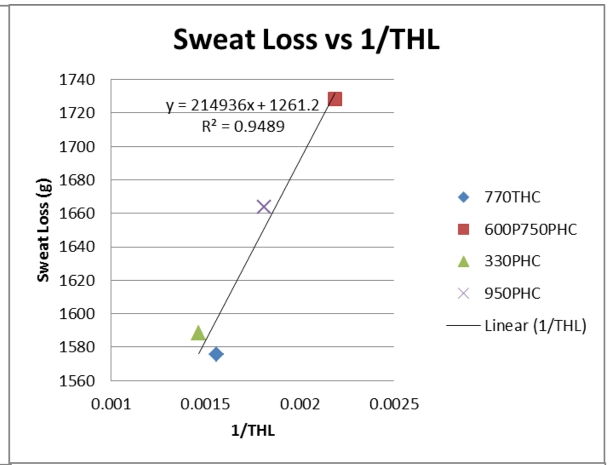
Max HR Rise vs Manikin THL
Max HR Rise (bpm)
Manikin THL (W/m2)
y = -0.1086x + 98.631
R² = 0.1538
770THC
600P750PHC
330PHC
950PHC
Linear (Manikin THL)

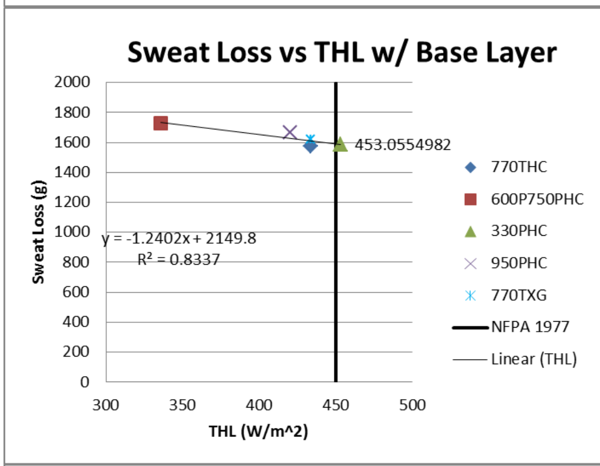


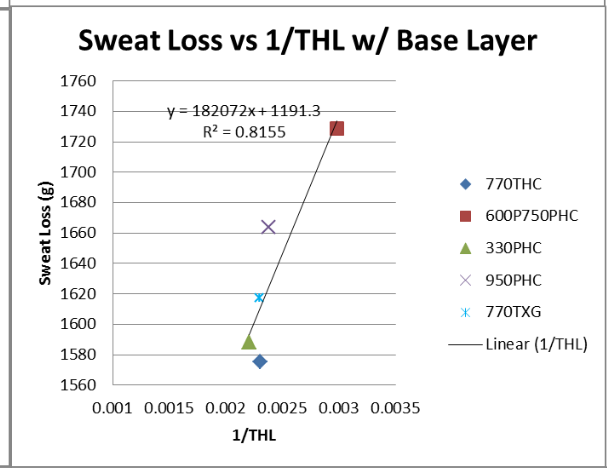
Max HR Rise vs 1/Manikin THL
Max HR Rise (bpm)
1/Manikin THL
y = 4461.6x + 54.396
R² = 0.179
770THC
600P750PHC
330PHC
950PHC
Linear (1/Manikin THL)

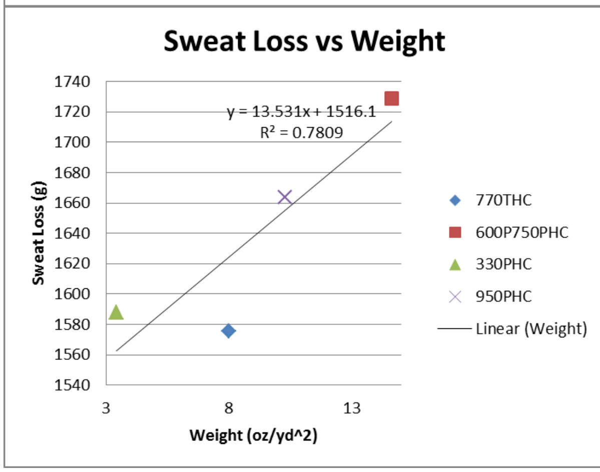
Total Sweat Loss Correlations:

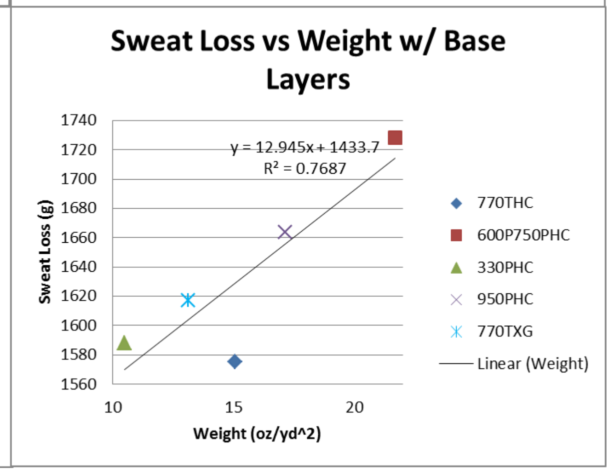


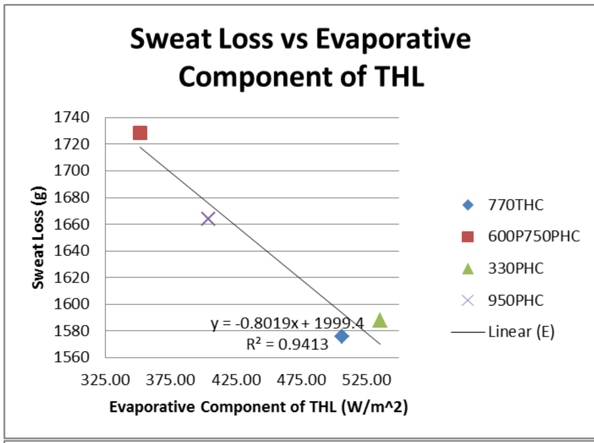


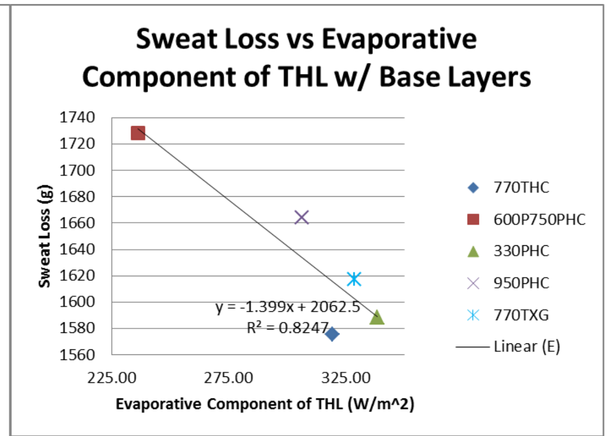


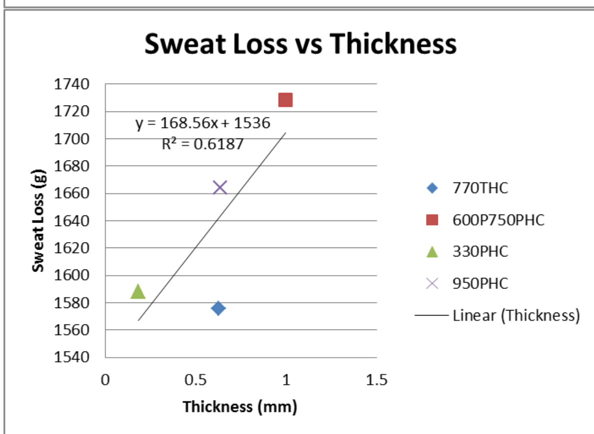


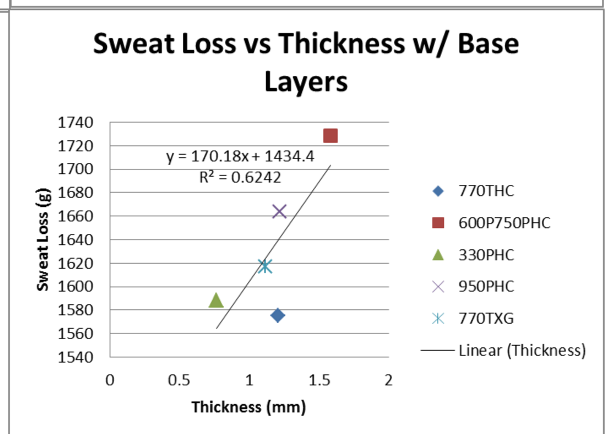


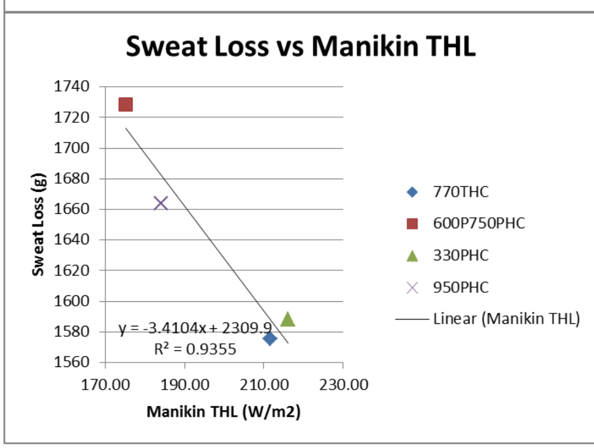


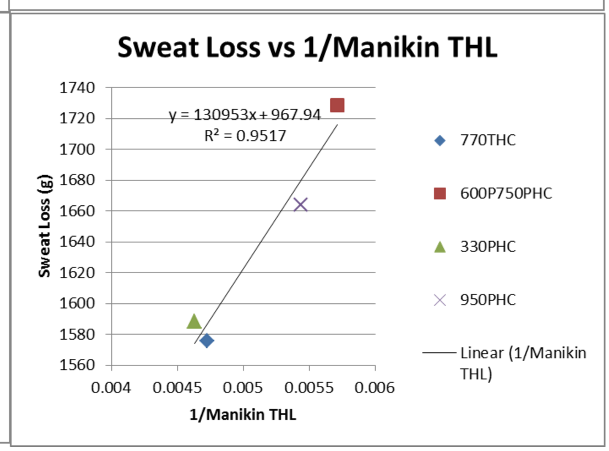

Sweat Loss vs Evaporative Component of THL
Sweat Loss (g)
1740
1720
1700
1680
1660
1640
1620
1600
1580
1560
y = -0.8019x + 1999.4
R² = 0.9413
325.00 375.00 425.00 475.00 525.00
Evaporative Component of THL (W/m^2)
770THC
600P750PHC
330PHC
950PHC
Linear (E)


Sweat Loss vs Evaporative Component of THL w/ Base Layers
Sweat Loss (g)
1740
1720
1700
1680
1660
1640
1620
1600
1580
1560
y = -1.399x + 2062.5
R² = 0.8247
225.00 275.00 325.00
Evaporative Component of THL (W/m^2)
770THC
600P750PHC
330PHC
950PHC
770TXG
Linear (E)

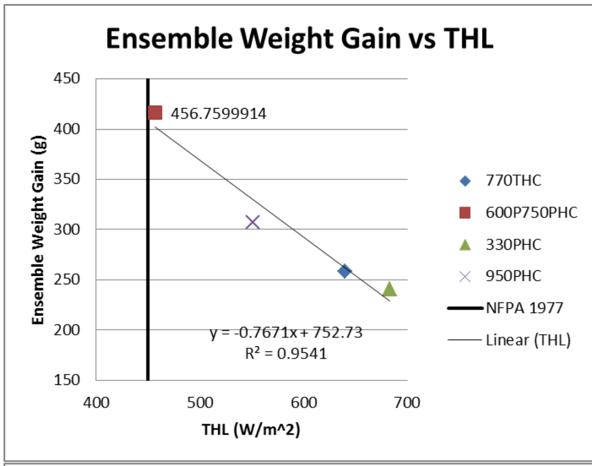

Sweat Loss vs Thickness
Sweat Loss (g)
1740
1720
1700
1680
1660
1640
1620
1600
1580
1560
1540
y = 168.56x + 1536
R² = 0.6187
0 0.5 1 1.5
Thickness (mm)
770THC
600P750PHC
330PHC
950PHC
Linear (Thickness)

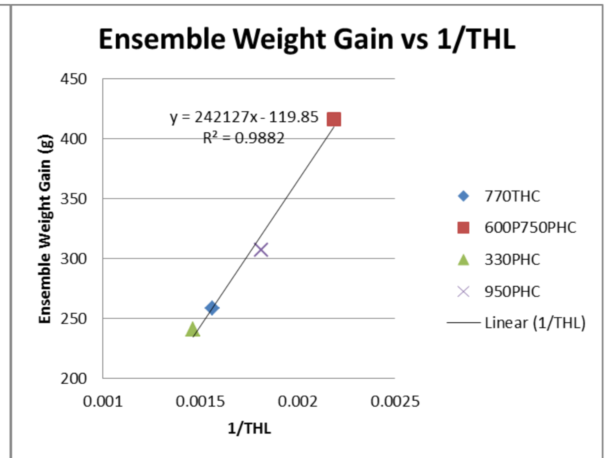

Sweat Loss vs Thickness w/ Base Layers
Sweat Loss (g)
1740
1720
1700
1680
1660
1640
1620
1600
1580
1560
1540
y = 170.18x + 1434.4
R² = 0.6242
0 0.5 1 1.5 2
Thickness (mm)
770THC
600P750PHC
330PHC
950PHC
770TXG
Linear (Thickness)

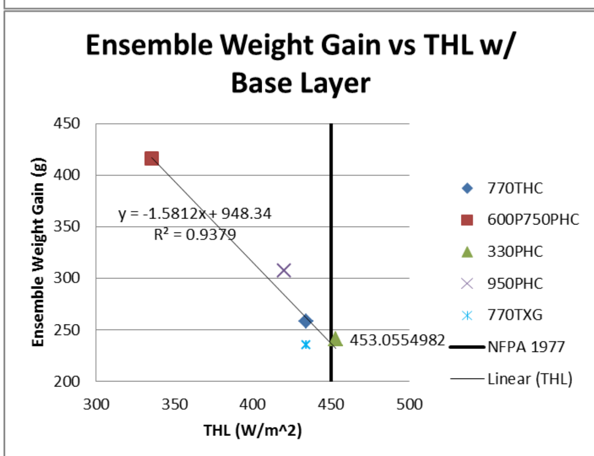

Sweat Loss vs Manikin THL
Sweat Loss (g)
1740
1720
1700
1680
1660
1640
1620
1600
1580
1560
y = -3.4104x + 2309.9
R² = 0.9355
170.00 190.00 210.00 230.00
Manikin THL (W/m2)
770THC
600P750PHC
330PHC
950PHC
Linear (Manikin THL)

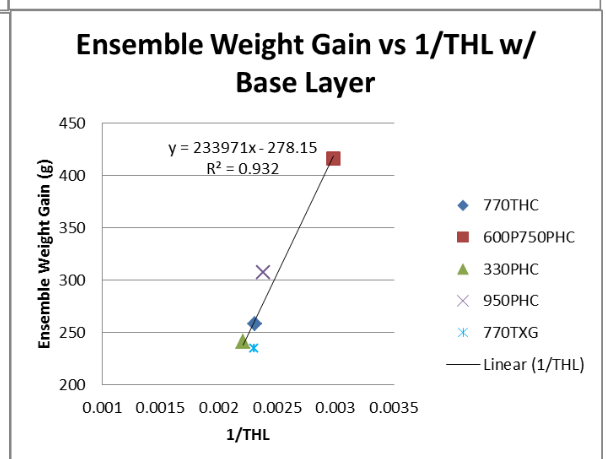

Sweat Loss vs 1/Manikin THL
Sweat Loss (g)
1740
1720
1700
1680
1660
1640
1620
1600
1580
1560
y = 130953x + 967.94
R² = 0.9517
0.004 0.0045 0.005 0.0055 0.006
1/Manikin THL
770THC
600P750PHC
330PHC
950PHC
Linear (1/Manikin THL)

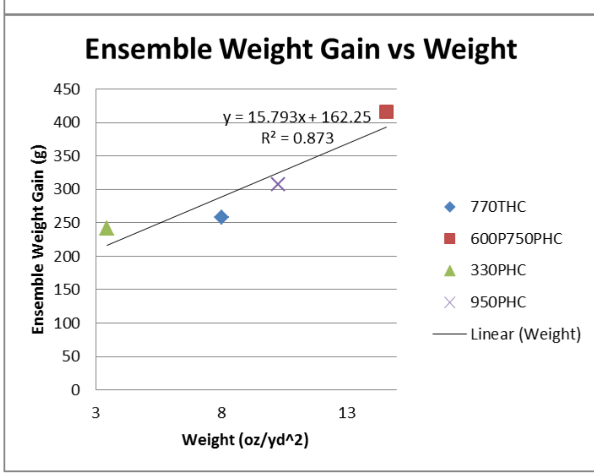
Ensemble Weight Gain Correlations:

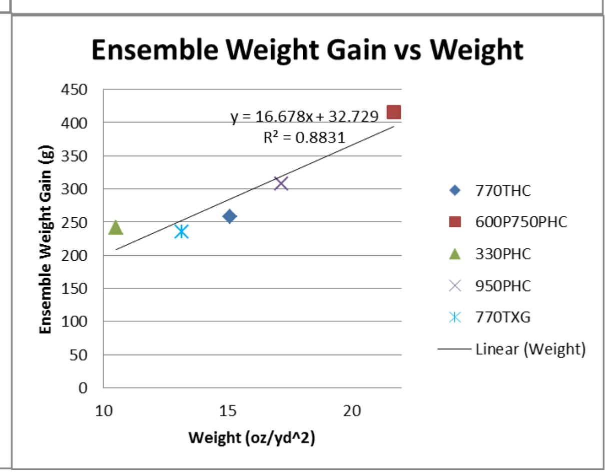


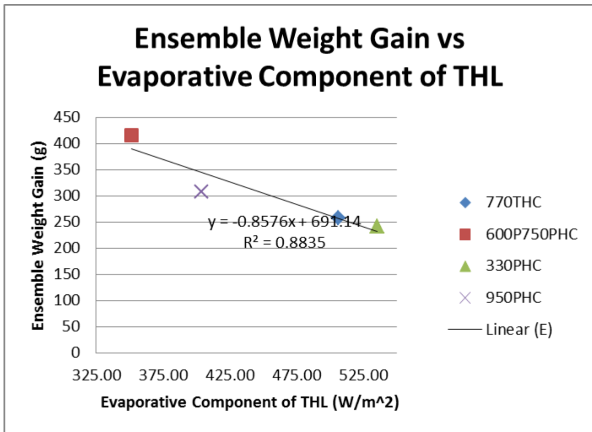


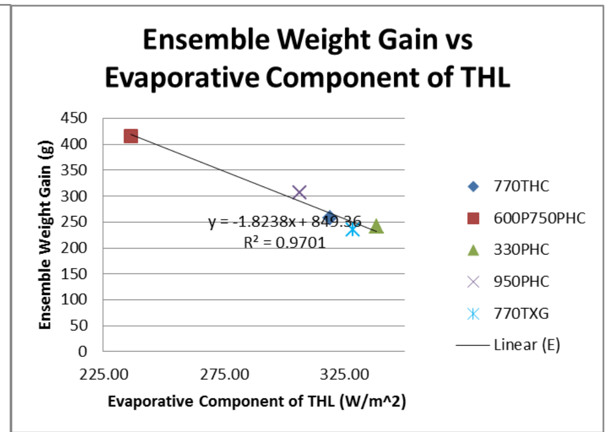


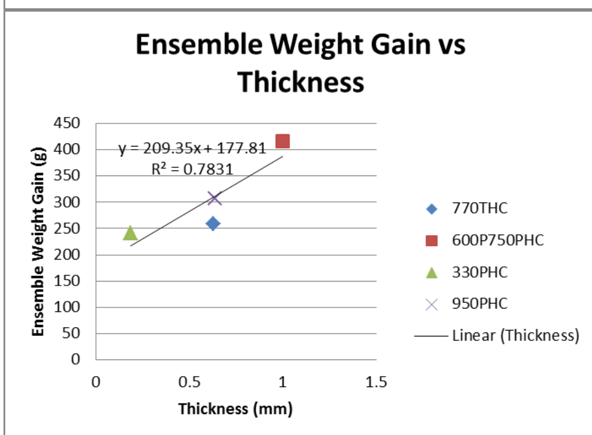


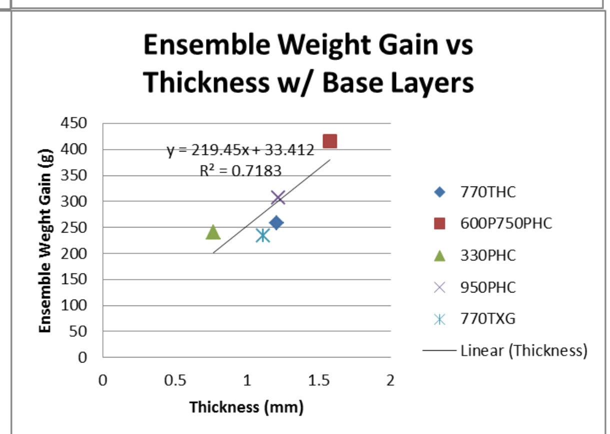


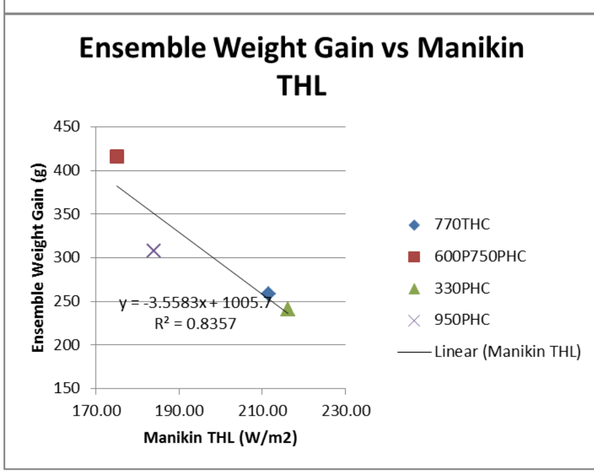


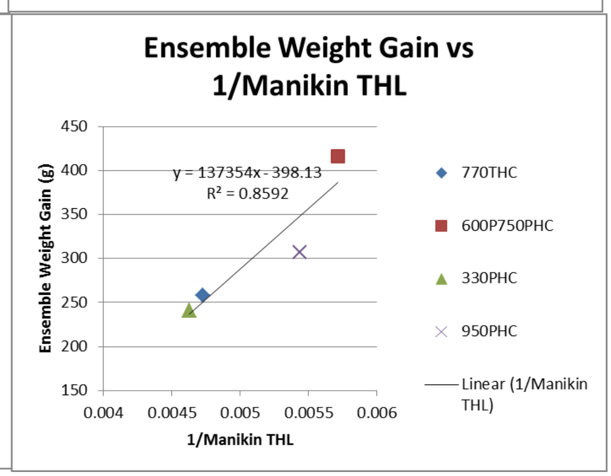

Ensemble Weight Gain vs Evaporative Component of THL
Ensemble Weight Gain (g)
450
400
350
300
250
200
150
100
50
0
325.00
375.00
425.00
475.00
525.00
Evaporative Component of THL (W/m^2)
y = -0.8576x + 691.14
R² = 0.8835
770THC
600P750PHC
330PHC
950PHC
Linear (E)


Ensemble Weight Gain vs Evaporative Component of THL
Ensemble Weight Gain (g)
450
400
350
300
250
200
150
100
50
0
225.00
275.00
325.00
Evaporative Component of THL (W/m^2)
y = -1.8238x + 849.36
R² = 0.9701
770THC
600P750PHC
330PHC
950PHC
770TXG
Linear (E)

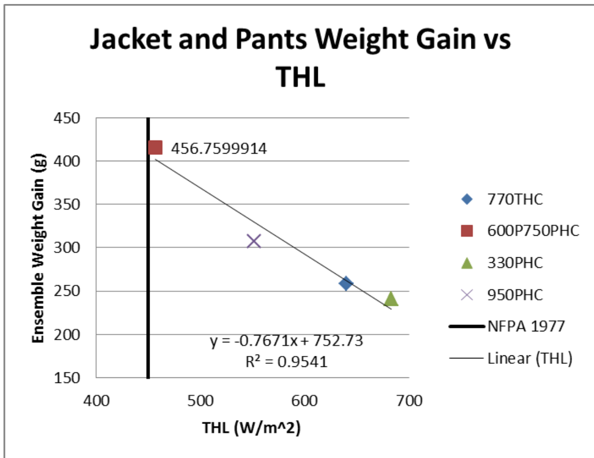

Ensemble Weight Gain vs Thickness
Ensemble Weight Gain (g)
450
400
350
300
250
200
150
100
50
0
0
0.5
1
1.5
Thickness (mm)
y = 209.35x + 177.81
R² = 0.7831
770THC
600P750PHC
330PHC
950PHC
Linear (Thickness)

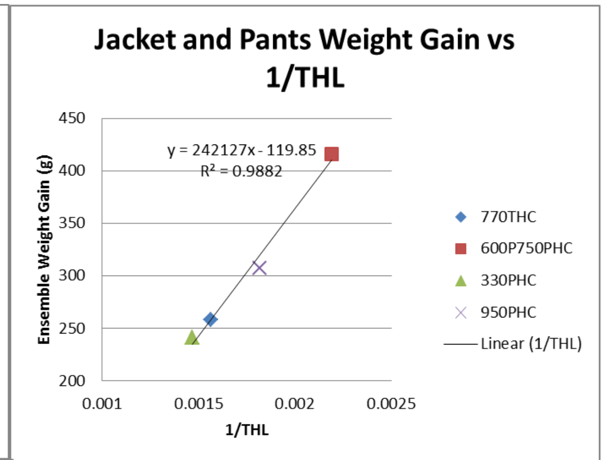

Ensemble Weight Gain vs Thickness w/ Base Layers
Ensemble Weight Gain (g)
450
400
350
300
250
200
150
100
50
0
0
0.5
1
1.5
2
Thickness (mm)
y = 219.45x + 33.412
R² = 0.7183
770THC
600P750PHC
330PHC
950PHC
770TXG
Linear (Thickness)

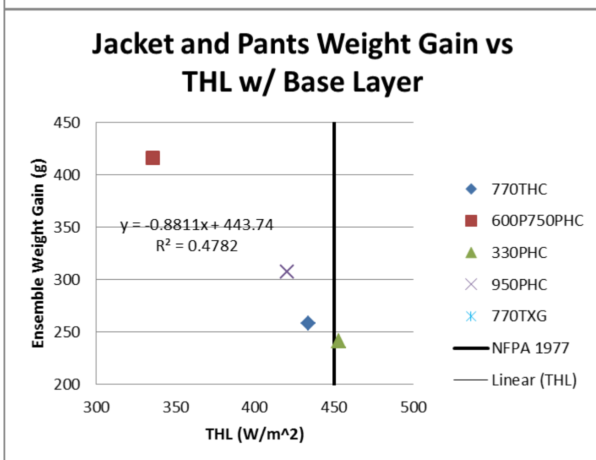

Ensemble Weight Gain vs Manikin THL
Ensemble Weight Gain (g)
450
400
350
300
250
200
150
170.00
190.00
210.00
230.00
Manikin THL (W/m2)
y = -3.5583x + 1005.7
R² = 0.8357
770THC
600P750PHC
330PHC
950PHC
Linear (Manikin THL)

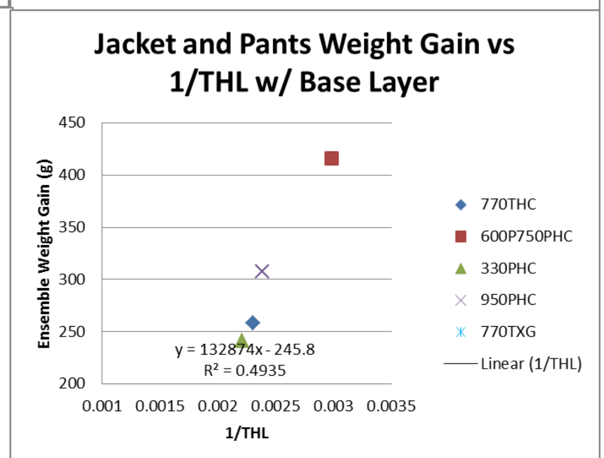

Ensemble Weight Gain vs 1/Manikin THL
Ensemble Weight Gain (g)
450
400
350
300
250
200
150
0.004
0.0045
0.005
0.0055
0.006
1/Manikin THL
y = 137354x - 398.13
R² = 0.8592
770THC
600P750PHC
330PHC
950PHC
Linear (1/Manikin THL)

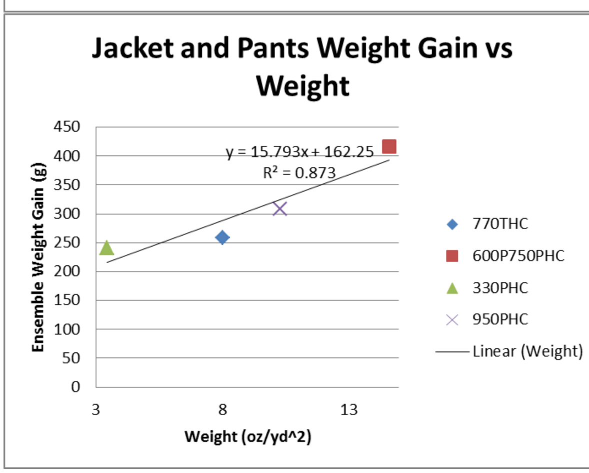
Jacket and Pants Weight Gain Correlations:

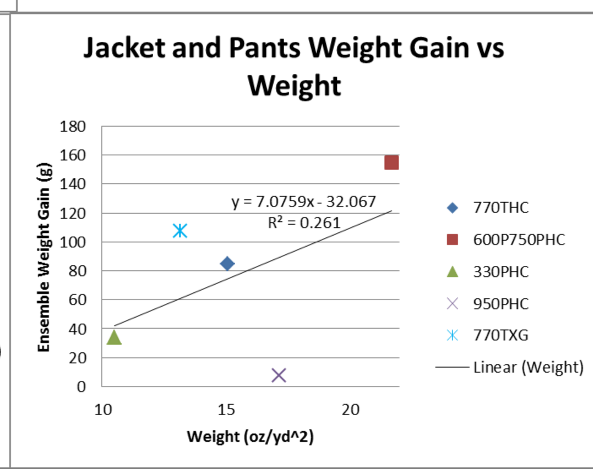


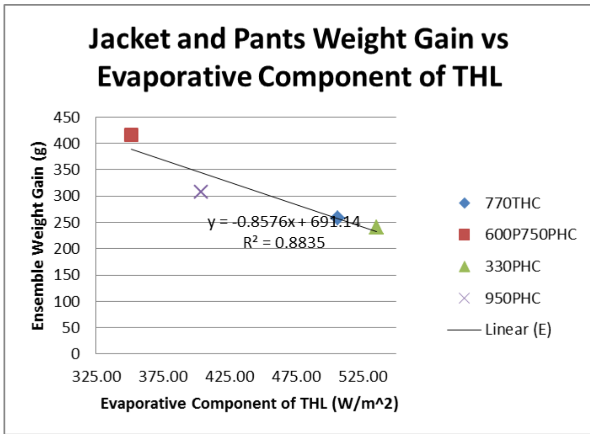


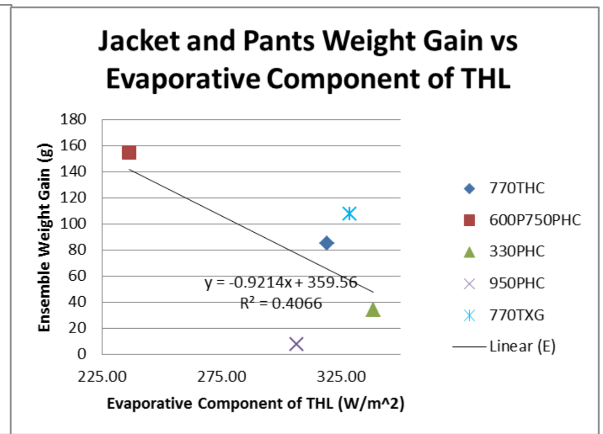


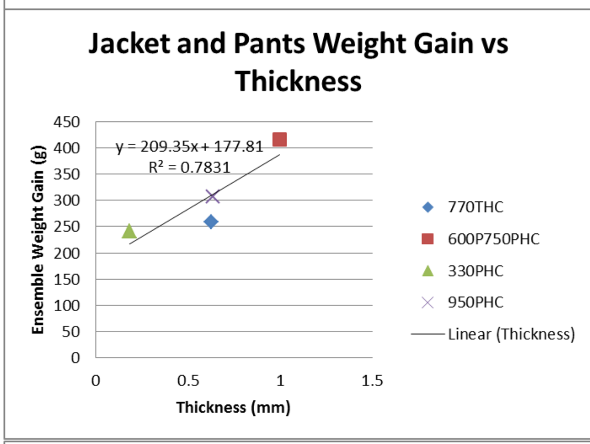


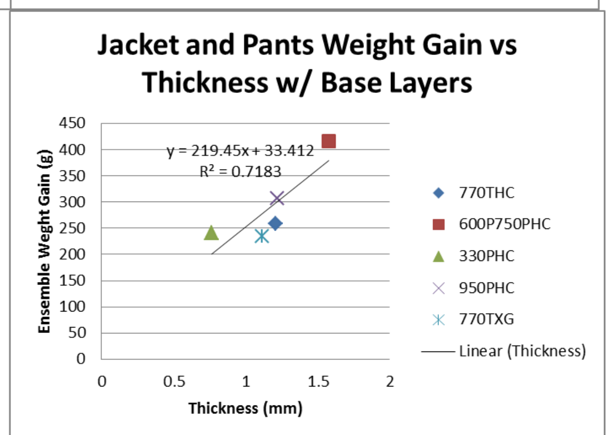


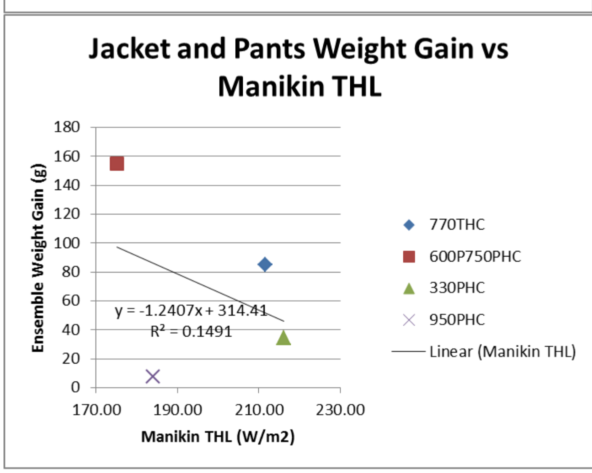


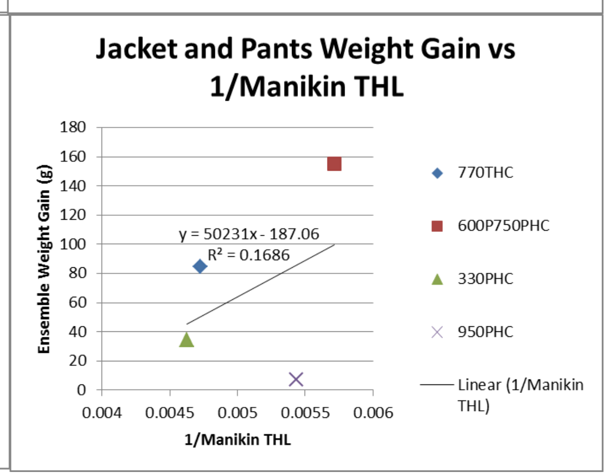

Jacket and Pants Weight Gain vs Evaporative Component of THL
Ensemble Weight Gain (g)
Evaporative Component of THL (W/m^2)
y = -0.8576x + 691.14
R² = 0.8835
770THC
600P750PHC
330PHC
950PHC
Linear (E)


Jacket and Pants Weight Gain vs Evaporative Component of THL
Ensemble Weight Gain (g)
Evaporative Component of THL (W/m^2)
y = -0.9214x + 359.56
R² = 0.4066
770THC
600P750PHC
330PHC
950PHC
770TXG
Linear (E)

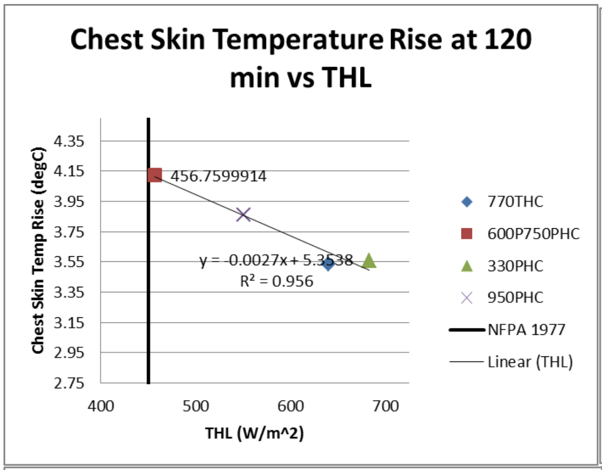

Jacket and Pants Weight Gain vs Thickness
Ensemble Weight Gain (g)
Thickness (mm)
y = 209.35x + 177.81
R² = 0.7831
770THC
600P750PHC
330PHC
950PHC
Linear (Thickness)

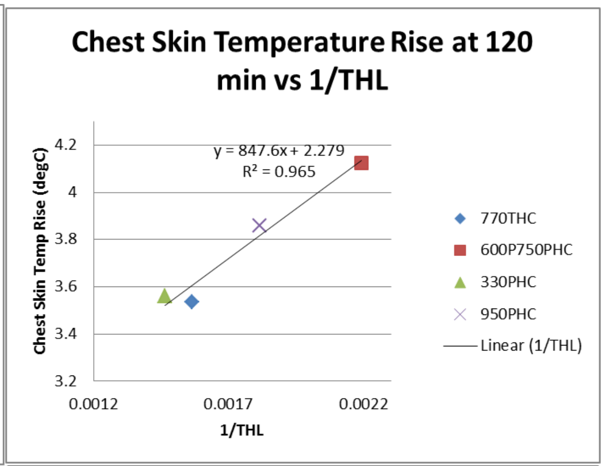

Jacket and Pants Weight Gain vs Thickness w/ Base Layers
Ensemble Weight Gain (g)
Thickness (mm)
y = 219.45x + 33.412
R² = 0.7183
770THC
600P750PHC
330PHC
950PHC
770TXG
Linear (Thickness)

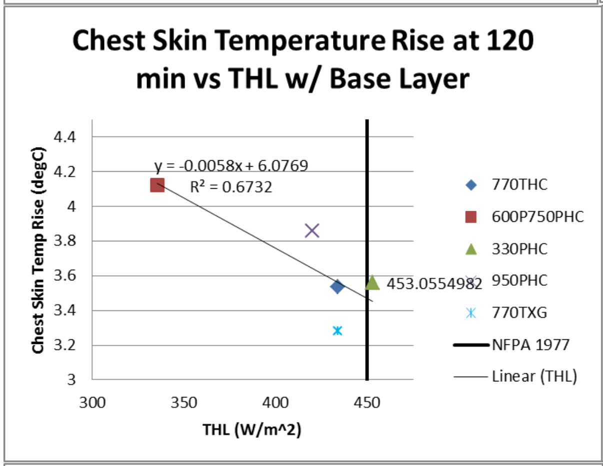

Jacket and Pants Weight Gain vs Manikin THL
Ensemble Weight Gain (g)
Manikin THL (W/m2)
y = -1.2407x + 314.41
R² = 0.1491
770THC
600P750PHC
330PHC
950PHC
Linear (Manikin THL)

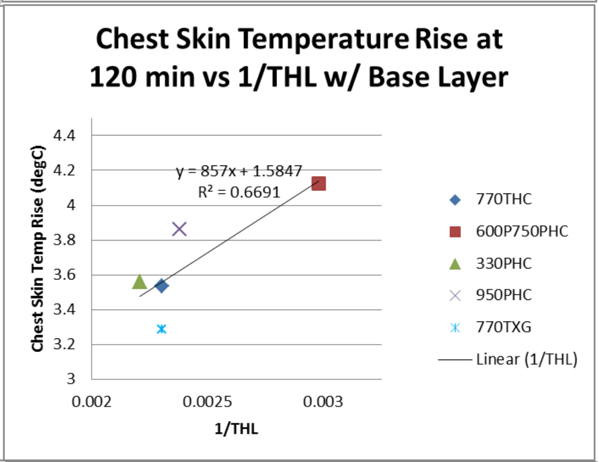

Jacket and Pants Weight Gain vs 1/Manikin THL
Ensemble Weight Gain (g)
1/Manikin THL
y = 50231x - 187.06
R² = 0.1686
770THC
600P750PHC
330PHC
950PHC
Linear (1/Manikin THL)

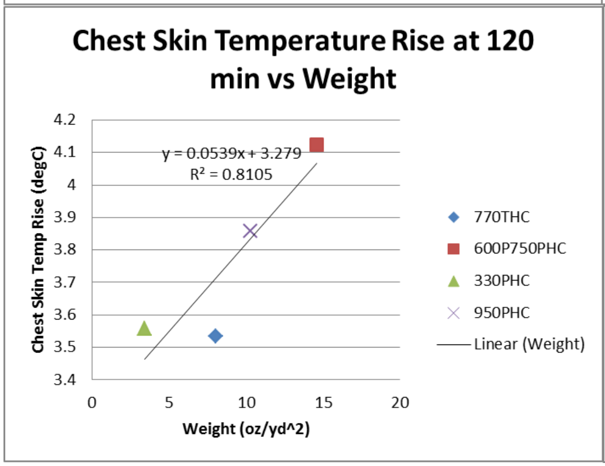
Chest Skin Temperature Correlations:

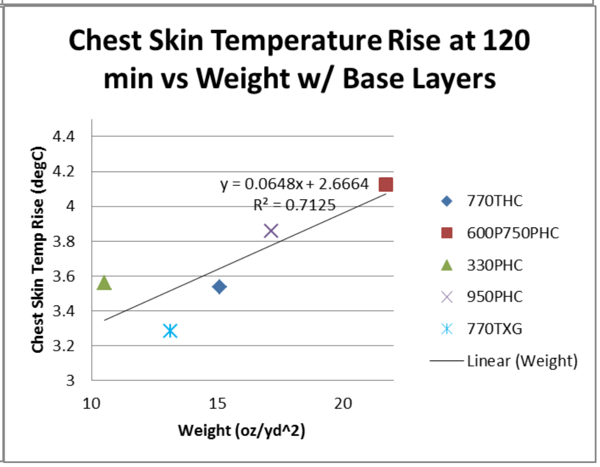


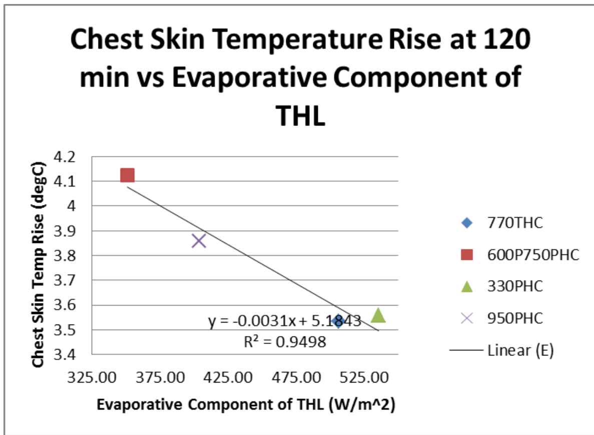


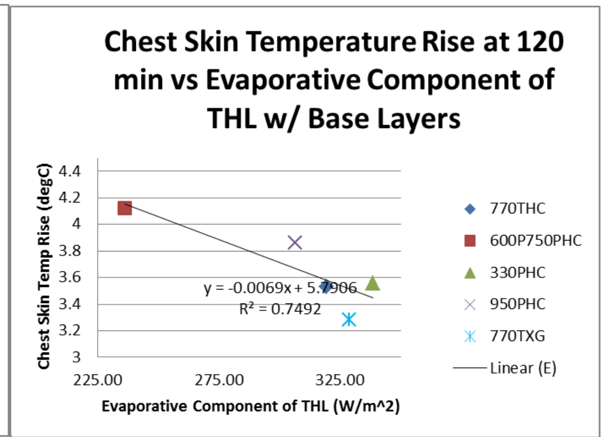


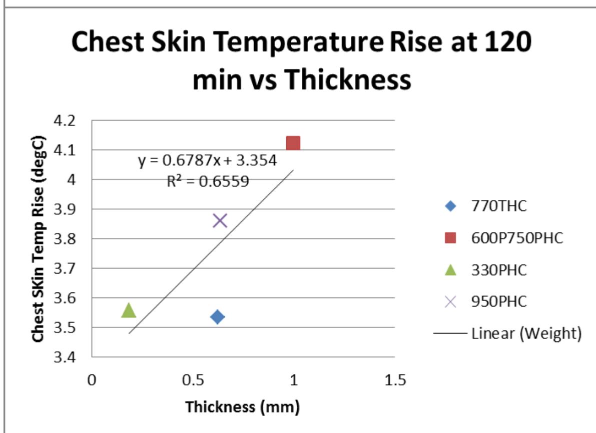


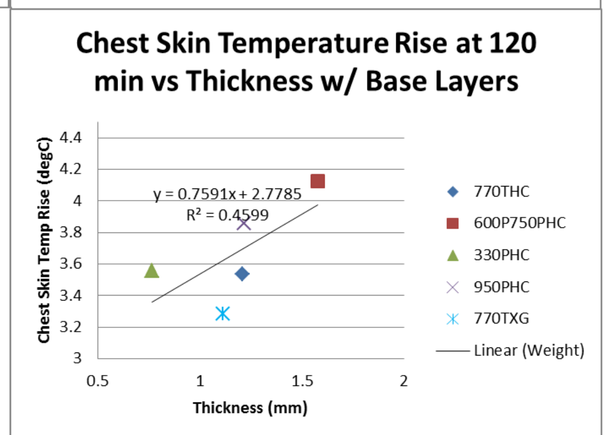


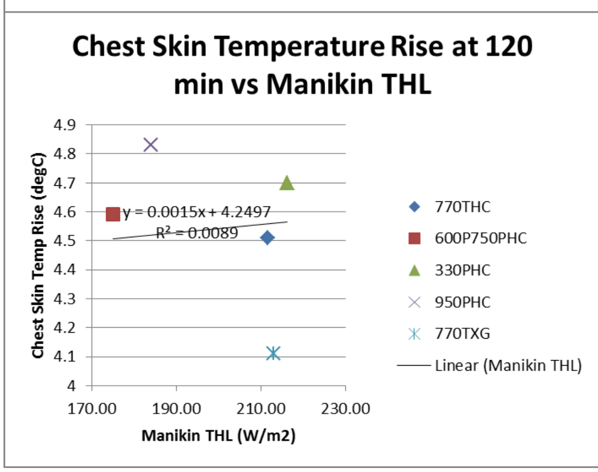


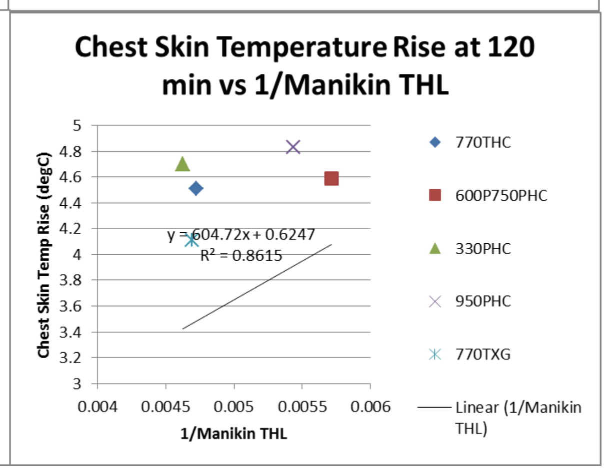

Chest Skin Temperature Rise at 120 min vs Evaporative Component of THL
Chest Skin Temp Rise (degC)
Evaporative Component of THL (W/m^2)
y = -0.0031x + 5.1843
R² = 0.9498
770THC
600P750PHC
330PHC
950PHC
Linear (E)


Chest Skin Temperature Rise at 120 min vs Evaporative Component of THL w/ Base Layers
Chest Skin Temp Rise (degC)
Evaporative Component of THL (W/m^2)
y = -0.0069x + 5.7906
R² = 0.7492
770THC
600P750PHC
330PHC
950PHC
770TXG
Linear (E)

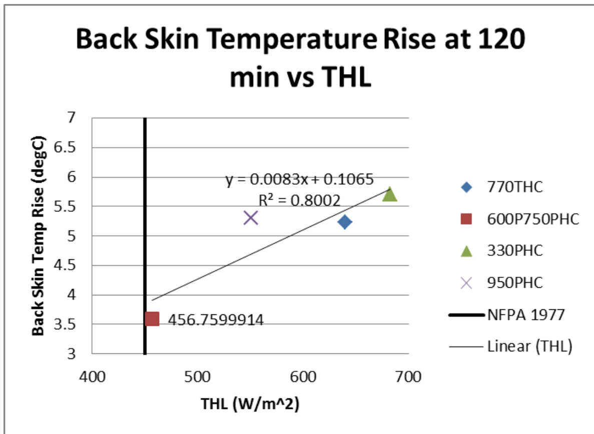

Chest Skin Temperature Rise at 120 min vs Thickness
Chest Skin Temp Rise (degC)
Thickness (mm)
y = 0.6787x + 3.354
R² = 0.6559
770THC
600P750PHC
330PHC
950PHC
Linear (Weight)

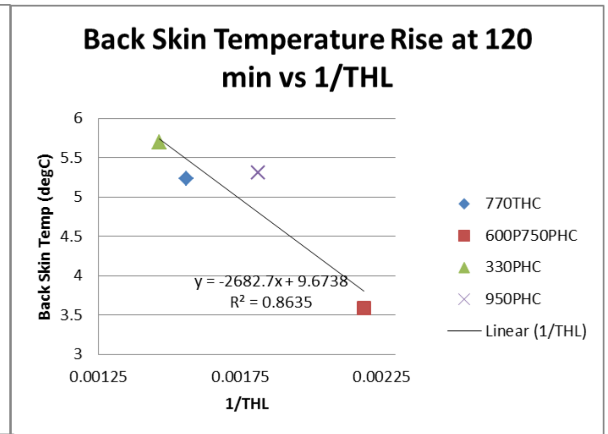

Chest Skin Temperature Rise at 120 min vs Thickness w/ Base Layers
Chest Skin Temp Rise (degC)
Thickness (mm)
y = 0.7591x + 2.7785
R² = 0.4599
770THC
600P750PHC
330PHC
950PHC
770TXG
Linear (Weight)

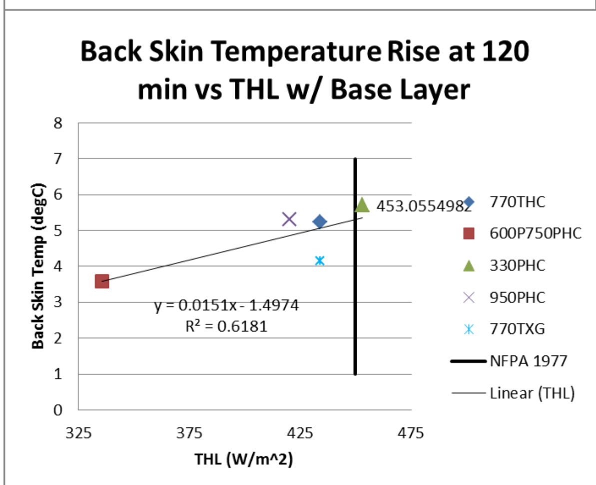

Chest Skin Temperature Rise at 120 min vs Manikin THL
Chest Skin Temp Rise (degC)
Manikin THL (W/m2)
y = 0.0015x + 4.2497
R² = 0.0089
770THC
600P750PHC
330PHC
950PHC
770TXG
Linear (Manikin THL)

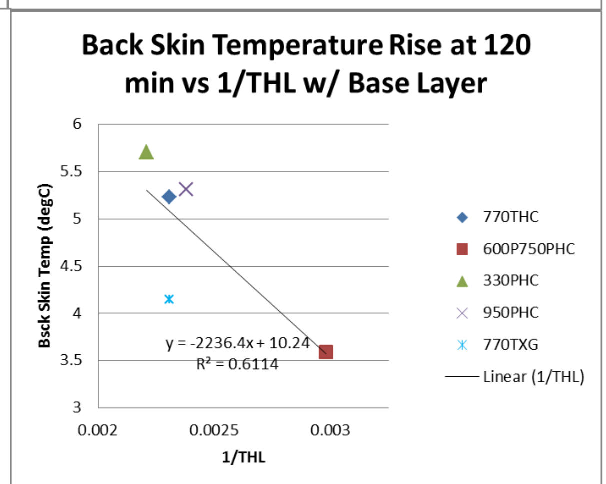

Chest Skin Temperature Rise at 120 min vs 1/Manikin THL
Chest Skin Temp Rise (degC)
1/Manikin THL
y = 604.72x + 0.6247
R² = 0.8615
770THC
600P750PHC
330PHC
950PHC
770TXG
Linear (1/Manikin THL)

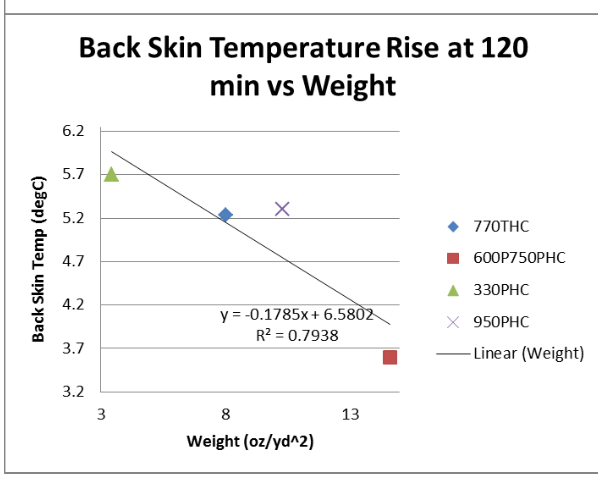
Back Skin Temperature at 120 min Correlations:

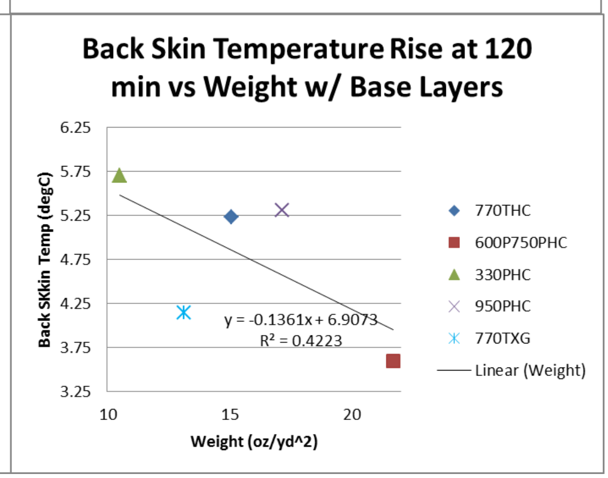


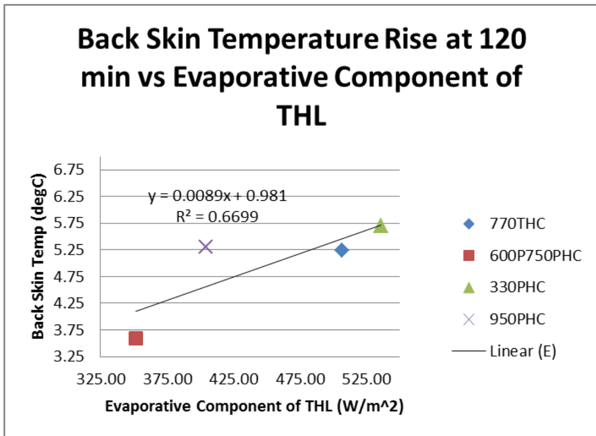


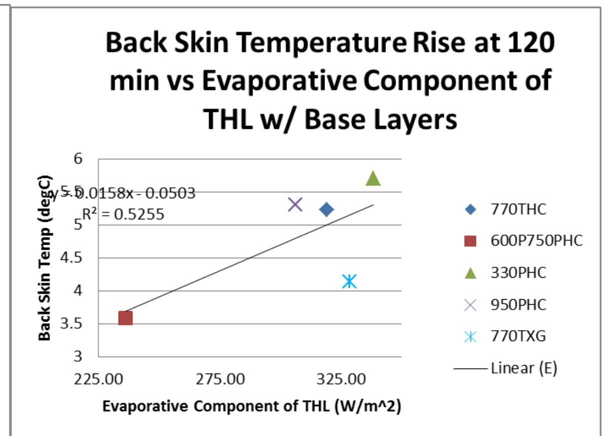


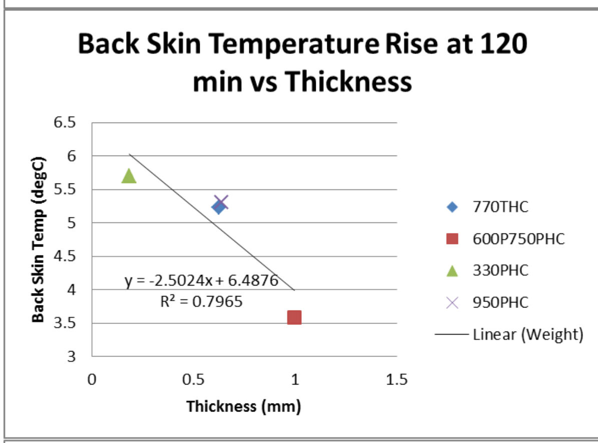


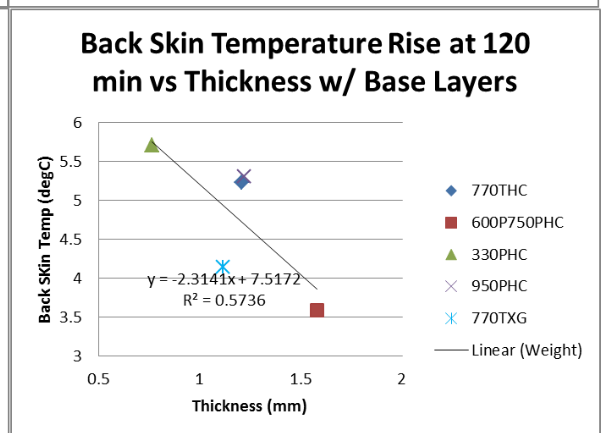


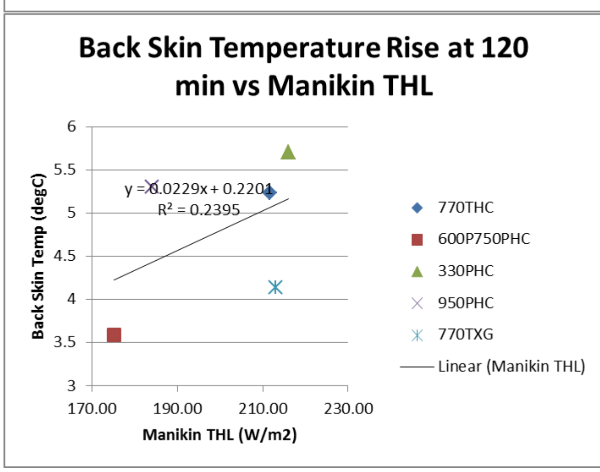


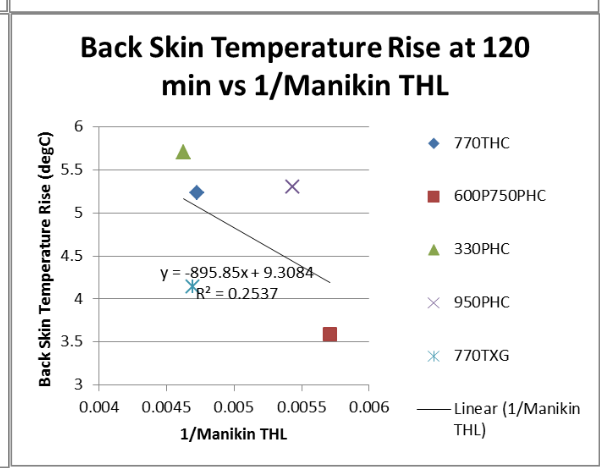

Back Skin Temperature Rise at 120 min vs Evaporative Component of THL
y = 0.0089x + 0.981
R² = 0.6699
Back Skin Temp (degC)
6.75
6.25
5.75
5.25
4.75
4.25
3.75
3.25
325.00 375.00 425.00 475.00 525.00
Evaporative Component of THL (W/m^2)
770THC
600P750PHC
330PHC
950PHC
Linear (E)


Back Skin Temperature Rise at 120 min vs Evaporative Component of THL w/ Base Layers
y = 0.0158x - 0.0503
R² = 0.5255
Back Skin Temp (degC)
6
5.5
5
4.5
4
3.5
3
225.00 275.00 325.00
Evaporative Component of THL (W/m^2)
770THC
600P750PHC
330PHC
950PHC
770TXG
Linear (E)


Back Skin Temperature Rise at 120 min vs Thickness
y = -2.5024x + 6.4876
R² = 0.7965
Back Skin Temp (degC)
6.5
6
5.5
5
4.5
4
3.5
3
0 0.5 1 1.5
Thickness (mm)
770THC
600P750PHC
330PHC
950PHC
Linear (Weight)


Back Skin Temperature Rise at 120 min vs Thickness w/ Base Layers
y = -2.3141x + 7.5172
R² = 0.5736
Back Skin Temp (degC)
6
5.5
5
4.5
4
3.5
3
0.5 1 1.5 2
Thickness (mm)
770THC
600P750PHC
330PHC
950PHC
770TXG
Linear (Weight)


Back Skin Temperature Rise at 120 min vs Manikin THL
y = 0.0229x + 0.2201
R² = 0.2395
Back Skin Temp (degC)
6
5.5
5
4.5
4
3.5
3
170.00 190.00 210.00 230.00
Manikin THL (W/m2)
770THC
600P750PHC
330PHC
950PHC
770TXG
Linear (Manikin THL)


Back Skin Temperature Rise at 120 min vs 1/Manikin THL
y = -895.85x + 9.3084
R² = 0.2537
Back Skin Temperature Rise (degC)
6
5.5
5
4.5
4
3.5
3
0.004 0.0045 0.005 0.0055 0.006
1/Manikin THL
770THC
600P750PHC
330PHC
950PHC
770TXG
Linear (1/Manikin THL)

Appendix I: Detailed Physiological Manikin Protocol

Test Period	Time (min mark)	MET rate	Activity Type	Activity
0	-30	1	0	Preheat manikin to thermo neutral in room outside chamber
1	0	1	0	Start test
2	10	2	1	Set manikin backwards on stand in chamber
3	11	3	1	
4	12	4	1	Hood shoes up for walking
5	13	5	1	Turn manikin walking on
6	60	3	1	Stop walking
7	61	1.2	1	Move manikin around (arms above head, elbow bends, knee lifts)
8	70	2	1	Start walking
9	71	3	1	
10	72	4	1	
11	73	5	1	
12	120	3	1	Stop walking and disconnect shoes
13	121	1.2	1	Move manikin around (arms above head, elbow bends, knee lifts)
14	130	1.2	1	Move manikin outside
15	140			End test, weigh clothing, dry manikin and clothing

Appendix J: Boundary Conditions file used in the RadTherm® Virtual Model

```
################################################################################
###
#            Human Comfort Module - Boundary Conditions File            #
################################################################################
###
#
# Description: This tab-delimited data file is used for specifying the boundary
#            conditions to be applied to the human thermoregulatory model.
#            Interpolation of the data will be performed between time steps.
#
# WARNING: This is a special data file in that it allows a variable number of
#         columns to be specified: The human comfort module will read the
#         column headers to determine which parameters to use for analysis.
#
# *ActLvl  (Activity level)    0.8 met         - basal metabolic rate
#                         1.0 met         - sitting quietly
#                        [2.0 - 4.0] met  - light physical activity
#                        [4.0 - 7.0] met  - moderate physical activity
#                        [8.0 - 12.0] met - vigorous intensity physical
#                                        activity
# *ActType (Activity type)     0 for Sedentary, 1 for Standing. This parameter
#                         will be used to properly distribute metabolic
#                         heating due to work. This parameter will
#                         not be interpolated for an unspecified time
#                         step.
#
################################################################################
###

Time	ActLvl	ActType
# [min]	[met]	[0-1]
0	1.0	0
9.9	1.0	0
10	2.0	1
10.9	2.0	1
11	3	1
11.9	3	1
12	4.0	1
12.9	4.0	1
13.0	5.0	1
59.9	5.0	1
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60.0	2.5	1
60.9	2.5	1
61	1.2	1
69.9	1.2	1
70	2	1
70.9	2	1
71.0	3	1
71.9	3	1
72.0	4	1
72.9	4	1
73.0	5	1
119.9	5	1
120	2.5	1
120.9	2.5	1
121	1.2	1
129.9	1.2	1
130	1.2	0
140	1.2	0