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Heat Stress Evaluation of Protective Clothing Ensembles

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Heat Stress Evaluation of Protective Clothing Ensembles

by

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A thesis submitted in partial fulfillment
of the requirements for the degree of
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heat stress protocol

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Dedication

I would like to dedicate this thesis manuscript to my family and friends. Without their support, encouragement and countless hours of communication from across the country my education and accomplishments would not have been possible.

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Heat Stress Evaluation of Protective Clothing Ensembles

Amanda Lee Pease

Abstract

Clothing directly affects the level of heat stress exposure. Useful measures to express the thermal characteristics are WBGT (wet bulb globe temperature) clothing adjustment factor (CAF) or apparent total evaporative resistance ($R_{e,T,a}$). The CAF is assigned through laboratory wear trials following a heat stress protocol in which the air temperature and humidity are progressively increased until the participant clearly loses the ability to maintain thermal equilibrium. The critical condition is the point of thermal transition and from these conditions both the CAF and $R_{e,T,a}$ are computed. The first objective of this study is to compare the thermal characteristics of a coverall made from a prototype fabric to work clothes and a commercial limited-use coverall using CAF and $R_{e,T,a}$. A second objective is to demonstrate that the $R_{e,T,a}$ of work clothes is the same for progressive or steady-state heat stress protocols.

Five participants (4 men and 1 woman) walked on a treadmill at 1.25 m/s at an average metabolic rate of 175 W/m². Each participant completed at least one progressive heat stress protocols in work clothes, Tyvek® 1422A coveralls [Tyvek® is a registered trademark of DuPont], and a developmental nonwoven polyolefin prototype ensemble provided by DuPont. In addition, four participants completed steady-state protocol in work clothes. Participants did not complete an acclimation period prior to the trials and each trial was separated by at least 40 hours.

There are no within participant differences in metabolic rate among ensembles and protocols. There are no differences between the critical WBGT in the current participants and previously acclimatized participants from other studies suggesting that the participants responded as if they were acclimatized. Based on a mixed effects model, there are significant differences between work clothes and Tyvek® 1422A for $R_{e,T,a}$ (0.0103 and 0.0141 m²/W kPa, respectively) and critical WBGT. The CAF for Tyvek is 2.3 °C-WBGT. For the DuPont prototype ensemble, the apparent total evaporative resistance is 0.013 m²kPa/W and the CAF is 0.5 °C. The prototype ensemble shows no difference from work clothes or Tyvek® 1422A in critical WBGT and no difference from work clothes in $R_{e,T,a}$. Overall, the prototype coveralls exhibited thermal characteristics that would have a lower level of heat stress than the Tyvek 1422A and not significantly different from work clothes.

The values for $R_{e,T,a}$ for work clothes were not different between the steady state and progressive protocols. The steady-state protocol near the critical condition can be used for determination of $R_{e,T,a}$. This opens up the possibility of estimating $R_{e,T,a}$ from studies that do not use the progressive protocol.

Chapter One

Introduction

Heat stress is a major occupational hazard in many industrial settings that can affect health and performance. The main risk factors associated with heat stress are the environment, metabolic demands, and clothing. An understanding of these factors and the underlying principles behind them is necessary when evaluating heat stress. Of particular interest to this study are the effects of protective clothing ensembles on heat stress.

The temperature of the human body is managed by thermal regulating mechanisms of heat exchange between the body and the surrounding environment. When an amount of heat gain occurs for which these mechanisms cannot compensate, core temperature can increase to dangerous levels. The thermal balance that occurs in the body can be described by the following equation²⁹.

$$S = M - W + C + R - E$$

Equation 1

All variables in this equation are expressed as rates (Watts) standardized over body surface area (m^2) i.e., $W m^{-2}$ ²⁸. In this equation, S is the rate of heat storage. If S is positive, the body is gaining heat. If S is negative, the body is losing heat. When the heat storage rate is zero ($S = 0$), there is a no heat gain or loss and the body is at thermal equilibrium. M is the metabolic rate. W is the external work performed by the body, which reduces the total heat burden²⁸. C is the convective heat exchange rate between the

body and the air. The radiant heat exchange is represented by R. E is the rate of evaporative heat loss due to sweating, which depends on air speed and vapor pressure. Evaporation is the central route of heat loss in high temperature environments. Other routes of heat exchange are conduction and respiration (both convection and evaporative).

Environmental factors can be described by basic climate parameters. One index metric commonly used to describe environmental factors in heat stress studies is the Wet Bulb Globe Temperature (WBGT). The WBGT can be calculated using the following equations.

$$\boxed{WBGT_{with..solar.load} = 0.7t_{nwb} + 0.2t_g + 0.1t_a} \quad \text{Equation 2}$$

$$\boxed{WBGT_{without.solar.load} = 0.7t_{nwb} + 0.3t_g} \quad \text{Equation 3}$$

For these WBGT equations, t_{nwb} is the natural wet bulb temperature, t_a is the air temperature and t_g is the globe temperature²⁸.

Metabolic rate affects heat production. The rate depends on the biochemical processes of the body and the energy needed to achieve the physical work⁹. External work (W) depends on the mechanical efficiency of the body. The total metabolic heat produced by the body (H) is

$$\boxed{H = M - W} \quad \text{Equation 4}$$

Finally, clothing can act as a barrier to heat exchange, which can greatly affect thermal balancing mechanisms. The amount of heat stress caused by clothes is influenced by the level of insulation, permeability and ventilation inherent to the fabric and construction of an ensemble. Insulation influences heat flow resistance and the rates of heat exchange through radiation, convection and conduction. Permeability shapes the movement of water vapor and affects evaporative resistance, which is directly connected to the rate of evaporative cooling. Ventilation influences the amount of air movement through and around clothing. This factor affects the rate of evaporation as well as the rate of convection. Overall, the apparent total evaporative resistance characterizes the ability of the clothing to support evaporative cooling. For WBGT-based evaluations, a Clothing Adjustment Factor (CAF) can be used to represent the effects of the clothing. This metric is a single number that is simply added to the environmental WBGT. The clothing adjustment factor is different for each type of ensemble. Because protective clothing affects heat stress, a control is to opt for ensembles with less evaporative resistance and lower CAF. Thus, comparative data are an important industrial hygiene tool in making decisions on protective clothing.

Chapter Two

Literature Review

Clothing Heat Transfer Models

The mechanisms of heat transfer through clothing can be conceptualized as two paths: dry heat transfer and moisture transfer. This two part model provides a conceptual and quantifiable method to assess the rates of heat transfer.

Dry heat transfer depends on the exchange of heat by conductive, convective and radiant heat and is driven by the temperature gradient between the skin and the environment. Values for dry heat transfer quantification can be determined from measurements using a heated flat plate or heated manikin. The parameter used to quantify dry heat transfer is the intrinsic clothing insulation (I_{cl}) and has units of $m^2 \text{ } ^\circ\text{C} / \text{W}$. This value is theorized to be independent of external conditions and specific to each garment. The dry heat transfer model attempts to measure the heat transfer from the body through the clothing layer to the environment and the resistance to that heat transfer. This value can be calculated from the thermal resistance of the air layer (I_a) and the total insulation (I_t). The total insulation is the additive insulation of the clothing and the boundary air layer ²⁸.

Moisture transfer is comprised of evaporative heat transfer and is driven by the difference in vapor pressure between the skin and the environment. The parameters used to quantify vapor transfer are the intrinsic evaporative resistance (R_{ecl}), the resistance of the air layer to the transfer of water vapor (R_{ea}) ²⁸. The intrinsic evaporative resistance quantifies the resistance of vapor transfer through the clothing to the environment. Both

the intrinsic evaporative resistance and the air layer resistance to transfer of water vapor have units of $\text{m}^2 \text{ kPa/W}$.

The evaporative resistance of clothing has the ability to impede the process of thermal regulation and decrease the amount of cooling through evaporation. Clothing and other protective layers that come between the skin and the environment have the ability to create a barrier. Depending on the permeability of the barrier, the amount of air movement and water vapor transport can be lessened. This affects the cooling mechanisms and can significantly reduce evaporative cooling.

Evaporation

Evaporation is a thermal regulatory mechanism used to cool the body. It is affected by air movement, humidity and clothing²⁹. This mechanism is supported by sweating and involves vaporization and mass transfer to the surrounding environment. Evaporation is the major method of dissipating heat from the body. In fact, as temperatures increase, evaporation becomes the only cooling mechanism¹⁵.

The evaporation rate required to keep the net heat storage at zero is the required evaporative cooling rate (E_{req}). This value is limited by the maximum evaporative cooling rate (E_{max}), which is affected by the environment and clothing factors. More specifically, this rate is influenced by the total evaporative resistance of the clothing. When the required evaporative cooling rate is less than the maximum evaporative cooling rate, the body can maintain thermal equilibrium. Beyond this point, the body can no longer thermoregulate and the heat stress is uncompensable³.

Ventilation

Dry heat and evaporative heat transfer can be enhanced by air movement through holes and openings in the clothing. Ventilation can decrease effective insulation and increased evaporative heat loss²⁸. This rate of exchange was first measured by Crockford using tracer gas techniques¹¹. The tracer gas technique was later expanded with the use of mass spectrometer detection, which simplified the procedure and decreased assessment time²⁴.

Parsons describes ventilation as the heat “transferred directly from the skin to the air through vents and openings in clothing,” which depend on the environment, skin, clothing, and activity performed. Parsons goes on to describe a scale that rates ventilation. This scale can be used to calculate the amount of energy leaving the body through ventilation, which can be added to the heat balance equation to determine required evaporation and more fully describe heat transfer²⁸. Additionally, ventilation can be determined experimentally using sealed clothing ensembles and trace gas technique or mass spectroscopy²⁸.

Progressive Heat Stress Protocol and Critical Conditions

One method used to determine the threshold of heat stress is the progressive protocol. In 1960, Lind outlined an experimental method that included a progressive increase from a cooler climate to a hotter climate, which would eventually result in heat stress²³. This method was later modified by Belding & Kamon in 1973 and Bernard & Kenney^{4, 5, 19}. Under this protocol, conditions that the body can thermally regulate are known as the prescriptive zone. As the environmental conditions progressively increase, the body is able to equilibrate at these increased levels until the upper limit of the

prescriptive zone (ULPZ) is reached. At the ULPZ, the body can no longer thermally regulate and there is an increase in heat storage. In other words, this is the maximum level at which an individual can safely perform a given task²³. The point before the upper limit of the prescriptive zone is defined as the critical condition. The critical condition is when maximum evaporative cooling is equally balanced by the net dry heat gain and internal sources¹⁰. The location of the critical condition is affected by the environment, metabolic rate and clothing.

There are variations of the progressive protocol. The first determines critical water vapor pressure by holding the dry bulb temperature constant and incrementally increasing the partial pressure of water vapor in the air every five minutes. The second method determines the critical air temperature by holding the partial pressure of water vapor in the air constant and increasing the dry bulb temperature every five minutes²⁸. The third is to hold relative humidity constant and increase temperature and vapor pressure every five minutes. The data collected from these methods can be used to determine critical conditions for clothing ensembles and the resistance to water vapor permeability²⁰.

Two important relationships are used with the heat stress protocol to calculate total apparent evaporative resistance and total clothing insulation^{2, 21}. Kenney used data from two critical conditions (warm, humid and hot, dry) and the following equations to determine $R_{e,T,a}$ and $I_{t,r}$ ²¹.

$$\frac{P_{sk} - P_a}{R_{e,T,a}} = H_{net} + \frac{T_{db} + T_{sk}}{I_{t,r}}$$

Equation 5

$$R_{e,T,a} = \frac{P_{sk} - P_a}{H_{net} + \frac{T_{db} - T_{sk}}{I_{T,r}}}$$

Equation 6

In these equations, P_{sk} is the saturated water vapor pressure at the skin. P_a is the saturated water vapor pressure in the atmosphere. $R_{e,T,a}$ is the apparent total evaporative resistance. H_{net} is the total metabolic heat produced by the body. T_{db} is the dry bulb temperature. T_{sk} is the temperature at the skin and $I_{T,r}$ is the resultant total insulation.

Resultant total insulation can also be estimated by using a heated manikin and the Standard Test Method for Measuring the Thermal Insulation of Clothing²³ and adjusting for air speed and activity using ISO9920¹⁸. In this case, only one condition is needed to solve for one unknown.

Clothing Adjustment Factors

The effect of clothing on individuals in the workplace can be assessed by the Clothing Adjustment Factor. The CAF was first introduced by Ramsey and further modified by Bernard, Kenney, Balint and O’Conner and Bernard to adjust environmental metrics when conditions necessitate work clothes that affect heat storage rates⁶. Factors that influence the Clothing Adjustment Factors include the insulation, ventilation and evaporative resistance of the ensemble. The units of the CAF are degrees-WBGT and this value is simply added to the measured WBGT of the environment. The combined WBGT and CAF is the Effective Wet Bulb Globe Temperature²⁹.

The Effective Wet Bulb Globe Temperature can be compared with recommended safe exposure levels from three sources; the National Institute of Occupational Safety and Health (NIOSH) Recommended Exposure Levels (REL), the American Conference of

Governmental Industrial Hygienist (ACGIH) Threshold Limit Values (TLV) and the United States Navy Physiological Heat Exposure Limit (PHEL)³.

Summary of Previous Study Results

There have been numerous studies focusing on the effects of heat stress and personal protective ensembles. An ensemble is can be tested to determine safe exposure limits to hot environments. Of particular interest in this study are trials that test work clothes and Tyvek ensembles to determine critical WBGT and $R_{e,T,a}$.

Work clothes, which consist of a long sleeve woven cotton shirt (135 g/m²) and pants (270 g/m²), are the control. This traditional cotton work garment is used by the ACGIH as a reference ensemble and has a CAF of 0 °C¹. The $R_{e,T,a}$ for work clothes was found to be 0.013 ± 0.003 by Caravello et al¹⁰ while the $WBGT_c$ for a moderate rate of work was 34.4 °C-WBGT by Bernard et al⁶.

Standard Tyvek® ensemble (1422A- 41 g/m²) [Tyvek® is a registered trademark of DuPont] is a useful comparison point for limited-use particle and light liquid splash barrier clothing. These ensembles can have a zipper front entry with elastic closures at the wrist, ankles and hood. Tyvek ensembles are water and vapor permeable. Bernard et al found the CAF for Tyvek 1424 ensemble (a fabric style slightly different to 1422A) to be 1 °C-WBGT with a $WBGT_c$ of 33.2 °C-WBGT⁶. The $R_{e,T,a}$ for Tyvek 1424 was 0.015 ± 0.004 by Caravello et al¹⁰.

Acclimatization State

Acclimatization occurs when the body becomes physiologically adapted to elevated levels of heat for prolonged daily periods. This affects heat tolerance levels and the amount of time an individual can safely perform tasks without the risks of heat stress.

Acclimatization can cause a decrease in initial rectal temperature and a decrease in the equilibrium level of both rectal temperature and heart rate¹². This process is due to increased sweat production, increased plasma volume and a fall in sodium chloride concentration in the blood, sweat and urine²⁸.

In 1993, Armstrong and Kenney examined the effects of acclimatization to passive heat exposure. Their protocol involved participants sitting in three thermal conditions before and after a nine day acclimatization period. Unlike other studies, the participants were matched for $V_{O_2 \max}$ and chronic activity. They found that acclimatization significantly lowered core temperature and the threshold for sweating onset².

In 1999, Stephen, Chang and Gonzalez examined the effects of acclimatization on chemical protective clothing. This group was interested in calculating the evaporative potential, which is “a measure of thermal insulation modified by moisture permeability” and can be used to compare the effects of acclimatization with difference ensembles. The results indicated that acclimatization can be beneficial against heat stress if the protective ensemble allows adequate evaporation. In addition, they developed an evaporative potential graph to predict the effects of acclimatization on heat stress reduction¹³.

Hypothesis

The purpose of this study is to determine $R_{e,T,a}$ and CAF for work clothes, Tyvek 1422A coveralls and coveralls of a prototype fabric using a progressive heat stress protocol. In addition, the use of participants wearing work clothes in a steady state protocol is examined. The null hypothesis is that there are no differences among (1) standard cotton work clothes, (2) Tyvek® 1422A coveralls (standard for particle and light

liquid splash protection) and (3) a DuPont prototype barrier coveralls. A second hypothesis is that there is no difference in computed $R_{e,T,a}$ for work clothes between progressive and steady state protocols.

Chapter Three

Methods

Participants

Five adults (four men and one woman) participated in the experimental trials. The mean and standard deviation of their physical characteristics by gender are provided in Table I. The study protocol was approved by the University of South Florida Institutional Review Board. A written consent was obtained prior to enrollment in the study. Each participant was examined by a physician and approved for participation. The participants were healthy, with no chronic disease requiring medication.

Table I: Physical Characteristics (mean \pm standard deviation)

	Number	Age (yr)	Height (cm)	Weight (kg)	Body Surface Area (m²)
Men	4	23.5 \pm 1.73	178 \pm 9	76.8 \pm 24.7	1.94 \pm 0.30
Women	1	21.0	168	57.0	1.64
All	5	23.0 \pm 1.87	176 \pm 9	72.8 \pm 23.1	1.88 \pm 0.29

Participants were reminded of the need to maintain good hydration. On the day of the trial, they were asked not to drink caffeinated beverages 3 hours prior to the appointment and not to participate in vigorous exercise before the trial.

There was no acclimatization period prior to beginning the experimental trials and there was at least a 40 hour break between trials.

Clothing

Three different clothing ensembles were evaluated. The ensembles included work clothes (136 g/m² cotton shirt and 271 g/m² cotton pants), standard Tyvek coveralls with

hood (Tyvek 1422A 41 g/m²) and a DuPont prototype coverall with hood (47 g/m² flashspun polyolefin with Frazier air permeability of 5 cfm/ft² (ASTM D737)). Both limited use coveralls had a zippered closure in the front, elastic cuffs at the arms, legs and attached hood.

A cotton T-shirt for men and sports bra with T-shirt for women and athletic shorts were worn under all clothing ensembles. Participants also wore socks and athletic shoes.

Equipment

The trials were conducted in a controlled climate chamber. The chamber floor space was 6 meters by 6 meters, had a temperature range between 4 °C and 60 °C and a relative humidity range between 10% and 90%. Temperature and humidity were controlled according to protocol and air speed was 0.5 m/sec. Heart rate was monitored using a sports type heart rate monitor (Polar Electro Inc, Lake Success, N.Y.). Core temperature was measured with a flexible thermistor inserted 10 cm beyond the anal sphincter muscle. The thermistor was calibrated prior to each trial using a hot water bath. The work demand consisted of walking at a speed of 1.25 m/sec on a motorized treadmill with no grade, which elicited a metabolic rate of about 175 W/m² to approximate moderate work. Assessment of oxygen consumption was used to determine metabolic rate. Participants breathed through a two-way valve connected to flexible tubing that was connected to a collection bag. Expired gas was collected for about 3 minutes. The volume of expired air was measured using a dry gas meter. A VacuMed Mini CPX oxygen analyzer was used to determine oxygen content of expired air. A metabolic rate was recorded for each trial and this value was the average of three samples of oxygen

consumption taken at approximately 30, 60 and 90 minutes into a trial and expressed as the rate normalized to body surface area.

Progressive Protocol

The study design called for one environment, which consisted of 50% relative humidity. Each ensemble was worn in this environment with a repeat trial of work clothes and a final constant exposure work clothes trial for a total of 5 trials. Participants completed one trial per day and had at least two days between trials. The order of ensembles was partially balanced. If there was a need to repeat a trial, it was repeated when the sequence of progressive exposures was completed.

Typically, the dry bulb temperature was set at 34 °C. Once the participant reached thermal equilibrium, the dry bulb temperature was increased 0.8 °C every five minutes until the trial was completed.

During trials, participants were allowed to drink water or a replacement fluid commercial beverage at will. Core temperature, heart rate and ambient conditions (dry bulb, psychrometric wet bulb and globe temperature) were monitored continually and recorded every five minutes. Trials were scheduled to last 120 minutes unless one of the following was met: (1) a clear rise in rectal temperature associated with a loss of thermal equilibration (typically 0.1 °C increase every 5 minutes for 15 minutes); (2) rectal temperature reached 39° C; (3) a sustained heart rate greater than 90% of the age-predicted maximum heart rate; or (4) participant wished to stop.

Steady-State Protocol

The second protocol was performed last with work clothes and a steady state protocol. The study design called for one environment, which consisted of 50% relative

humidity. The dry bulb temperature was determined as the inflection point from the progressive protocol trial in work clothes. The humidity and dry bulb temperature were steady throughout the final trial. The treadmill speed was the same as the progressive protocol.

Inflection Point and Calculation of Apparent Total Evaporative Resistance

The inflection point marks the transition from thermal balance to the loss of thermal balance, where core temperature continued to rise. The chamber conditions five minutes before the noted increase in core temperature was taken as the critical conditions.

Calculation of Clothing Parameters

The apparent total evaporative resistance was computed as follows. In the current study, resultant total insulation was treated as a fixed value for all ensembles and was estimated according to ISO 9920¹⁸ as

$$CFI = e^{-0.281(v-0.15)+0.044(v-0.15)^2-0.492w+0.176w^2}$$

Equation 7

where air speed (v) was taken as 0.5 m/sec and walking speed (w) was the treadmill speed (m/sec) for the specific trial. This adjustment for air and body movement was similar to that proposed by Holmer et al¹⁷. The value of resultant clothing insulation was further reduced by 10% (multiplied by 0.9) to account for the reduction in insulation due to wetting⁸.

$$I_{T,r} = CFI \cdot I_{T,stat} \cdot 0.9$$

Equation 8

Equation 6 was used to calculate $R_{e,T,a}$. Referring to Kenney et al, the measurements in this equation were computed as follows³. Metabolic rate (M) in W/m^2 was estimated from oxygen consumption in liters per minute as $M = 350 V_{O_2}/A_D$. The Dubois surface area (A_D) was calculated as

$$A_D = 0.202m_b^{0.425} * H^{0.725} \quad \text{Equation 9}$$

where m_b was the mass of the body (kg) and H was the height (m). The external work (W_{ext}) was calculated (W/m^2) as

$$W_{ext} = 0.163m_b * V_w * f_g / A_D \quad \text{Equation 10}$$

where V_w was walking velocity in m/min and f_g was the fractional grade of the treadmill. Respiratory exchange, latent respiration heat loss (E_{res}) and dry respiration heat loss (C_{res}), were calculated as

$$C_{res} = 0.0012M(T_{db} - 34) \quad \text{Equation 11}$$

$$E_{res} = 0.0173M(5.62 - P_a) \quad \text{Equation 12}$$

To account for a gradual change in T_{re} , the rate of change in heat storage was determined from the specific heat of the body ($0.97 W h/^\circ C kg$), body weight (m_b), and the rate of

change of body temperature ($\Delta T_{re} \Delta t^{-1}$) as an average of the 20 minutes preceding the inflection point. That is

$$S = 0.97 m_b \Delta T_{re} A_D^{-1} \Delta t^{-1}$$

Equation 13

This approach was taken by Barker et al. (1999) with some changes in sign conventions employed³.

The apparent total evaporative resistance was computed by arranging previous equations to the following equation where P_{sk} was the saturated pressure of water vapor at T_{sk} .

$$R_{e,T,a} = \frac{P_{sk} - P_a}{H_{net} + \frac{T_{db} - T_{sk}}{I_{T,r}}}$$

Equation 14

Chapter Four

Results

Table II illustrates the protocols completed by each participant. There were four progressive heat stress trials for which a critical condition was not found, but a value for $R_{e,T,a}$ was computed. Participant 2 did not attempt a second work clothes trial or the final steady-state trial.

Table II: Completed Trials by Participant

Participant	Work Clothes 1	Work Clothes 2	Tyvek 1422A	Prototype	Work Clothes – Steady-State
1	1	+1	1	1	1
2	1	--	1+1	1+1	--
3	1	1	1	1	1
4	1	1	1	1	1
5	1	1	1+1	1	1

+1: means that a critical condition was not found because the trial was stopped without an inflection point. $R_{e,T,a}$ was computed from the last recorded data point.

The average metabolic rates by ensemble and protocol are summarized in Table III. Also included in Table III are the $WBGT_c$ for the progressive protocols and $R_{e,T,a}$ for all protocols.

Table III: Metabolic Rate, Critical WBGT and Apparent Total Evaporative Resistance (mean \pm standard deviation) by Ensemble and Protocol

Ensemble	Protocol	Metabolic Rate (W/m ²)	WBGT _c (°C)	$R_{e,T,a}$ (m ² kPa /W)
Work Clothes	Progressive	175 \pm 27	35.5 \pm 1.4	0.0110 \pm 0.003
Work Clothes	Steady State	176 \pm 27	-	0.0119 \pm 0.003
Tyvek®				
1422A	Progressive	166 \pm 26	33.7 \pm 1.0	0.0151 \pm 0.004
Prototype	Progressive	180 \pm 19	35.0 \pm 1.7	0.0113 \pm 0.002

Metabolic Rate

To assess potential differences in metabolic rate among the four combinations of ensembles and protocols, a mixed effects model was used. The fixed effect was the combination of ensemble and protocol and the random effect was participants. There was no significant difference in metabolic rate among the combinations of ensembles and protocols ($p = 0.8$).

Acclimatization State

Because the current participants were not acclimatized, a comparison to acclimatized participants was undertaken. A two sample t-test with different sample sizes was performed to assess $R_{e,T,a}$ and $WBGT_c$ between acclimatized participants from previous studies ($n=15$) and the current participants ($n=5$) for work clothes and Tyvek® 1424 and 1422A ensembles, respectively. The acclimatized $WBGT$ values were from Bernard et al and were adjusted for metabolic rate using the slope of -0.039 °C- $WBGT/W/m^2$ found for combined ensembles⁷. The acclimatized $R_{e,T,a}$ values were from Caravello¹⁰. There was no significant difference between the acclimatized population and the current population of participants in $R_{e,T,a}$ for either ensemble (WC: $t = 1.44$, Tyvek: $t = 0.00$) and no significant difference in $WBGT_c$ for Tyvek ensemble ($t = 0.87$). There was a significant difference in $WBGT_c$ for work clothes ($p < 0.05$), where the unacclimatized participants were unexpectedly higher. Table IV summarizes the results.

Table IV: WBGT_c and R_{e,T,a} for Work Clothes and Tyvek (mean ± standard deviation) for Acclimatized and Unacclimatized Participants

Ensemble	WBGT _c		R _{e,T,a}	
	Unacclimatized	Acclimatized	Unacclimatized	Acclimatized
WC	36.0 ± 0.58	34.2 ± 1.2	0.011 ± 0.001	0.013 ± 0.003
Tyvek *	33.7 ± 0.53	33.2 ± 1.2	0.015 ± 0.002	0.015 ± 0.004

* Tyvek® refers to 1424A for acclimatized and 1422A for unacclimatized.

Ensembles

A mixed effects model was used to assess WBGT_c and R_{e,T,a} among the three ensembles for the progressive protocols. Participants were treated as a random effect. There were significant differences among WBGT_c ($p < 0.05$) and R_{e,T,a} ($p < 0.05$) by ensemble. For WBGT_c, a Tukey's honestly significant difference test at $\alpha = 0.05$ found that work clothes and Tyvek® 1422A were different from each other, but that there was no difference between the DuPont prototype and either work clothes or Tyvek® 1422A. For R_{e,T,a}, a Tukey's honestly significant difference test at $\alpha = 0.05$ found that Tyvek® 1422A was significantly different from the DuPont prototype ensemble and the work clothes but that there was no significant difference between the work clothes and the prototype ensemble.

Progressive and Steady State Protocol

A mixed effects model was performed to assess R_{e,T,a} of work clothes between the progressive protocol and the steady state protocol. There was no significant difference between the two protocols ($p = 0.6$).

Chapter Five

Discussion

Metabolic Rate

One experimental control was the metabolic rate normalized to body surface area. No significant differences were found for metabolic rate among the combinations of ensembles and protocols, which supports adequate control of metabolic rate and thus no systematic effect on $WBGT_c$ or $R_{e,T,a}$.

Acclimatization State

The $WBGT_c$ for work clothes from the current study was 35.5 °C-WBGT. There are two previous studies that have examined unacclimatized participants. These studies are summarized in Table V^{23,22}. Lind used semi-nude participants and the ULPZ protocol at 350 W, which is comparable to the metabolic rate of the current protocol (329 W). The ULPZ was 28.2 °C-WBGT and can be adjusted for the semi-nude state to clothed by subtracting 2 °C-WBGT. This results in an adjusted ULPZ of 26.2 °C-WBGT, which is less (9.3 °C-WBGT) than the current $WBGT_c$. Kenney et al determined the $WBGT_c$ for unacclimatized participants with a metabolic rate of 190 W/m². This was adjusted for metabolic rate using the slope of -0.039 °C-WBGT /W/m² found by Bernard et al for combined ensembles⁷ and further adjusted for semi-clothed state by subtracting 2 °C-WBGT. This final adjusted $WBGT_c$ of 30.0 °C is also less (4.5 °C-WBGT) than the current $WBGT_c$. These lower $WBGT_c$ s suggest that the participants in the current study did not respond as other unacclimatized participants.

Table V: Summary of WBGT_c for Unacclimatized Participants

	WBGT _c (°C)	Adjusted WBGT _c (°C)
Lind (1963)	28.2	26.2
Kenney (2002)	31.2	30.0

In this study, the WBGT_c using unacclimatized participants was 35.5 °C-WBGT for work clothes and 33.7 °C-WBGT for the Tyvek® 1422A ensemble. Table VI summarizes the WBGT_c from previous studies using acclimatized participants. The differences in WBGT_c for this study and the previous studies range from 0.7 °C-WBGT to 1.3 °C-WBGT for work clothes and 0.3 to 1.1 °C-WBGT for Tyvek. Some of the differences could be due to the differences in Tyvek fabrics tested. It is more likely that the differences are random. Bernard et al⁷ reported a standard error of mean at 1.6 °C-WBGT, which is greater than the differences in WBGT_c among the studies. This indicates that our participants responded as acclimatized participants. While there was no formal acclimatization period prior to the trials, the participants may have been acclimatized by virtue of their daily exercise activities in Central Florida, even in the cooler months in which these trials were run.

Table VI: WBGT_c Values for Work Clothes and Tyvek Ensemble

	WBGT _c		Ensemble
	Work Clothes (°C)	Tyvek (°C)	
Current Study	35.5	33.7	Tyvek 1422A
O'Conner 1999	34.2	32.6	Tyvek 1422A
Bernard 2005	34.5	33.4	Tyvek 1424
Bernard 2008	34.8	34.1	Tyvek 1424/1427

Comparisons among Ensembles

The progressive protocol is well established as a method to determine CAF and $R_{e,T,a}$. Statistical analysis indicated that work clothes and Tyvek® 1422A were statistically different. The baseline for comparison is the $WBGT_c$ for work clothes, which was 35.5 °C-WBGT. The $WBGT_c$ for Tyvek® 1422A was 33.7 °C-WBGT, which corresponds to a clothing adjustment factor of 1.8 °C-WBGT. Table VII summarizes the CAF from previous studies, which range from 0.7 to 2 °C-WBGT. The lower values of CAF found by Bernard et al^{6,7} were expected due to the different fabric styles used in the Tyvek ensembles. The CAF reported by O’Conner and Bernard was for the same fabric (1422A).

Table VII: CAF Values for Tyvek Ensemble

	CAF (°C)	Ensemble
Pease	1.8	Tyvek 1422A
O’Conner	2.0	Tyvek 1422A
Bernard 2005	0.8	Tyvek 1424
Bernard 2008	0.7	Tyvek 1424/1427

The $WBGT_c$ for the DuPont prototype ensemble was 35.0 °C-WBGT, which corresponds to a clothing adjustment factor of 0.5 °C-WBGT. This value puts the prototype ensemble in between the work clothes and the Tyvek® 1422A ensemble (2.0 °C-WBGT). Statistical analysis indicated that the $WBGT_c$ for prototype ensemble was not different from either work clothes or Tyvek® 1422A ensemble, which reinforces the inference that the CAF for the DuPont prototype is between the baseline work clothes and the Tyvek® 1422A ensemble.

The apparent total evaporative resistance was 0.011 m²kPa/W for work clothes and 0.015 m²kPa/W for the Tyvek® 1422A ensemble. These values were statistically different. Table VIII provides the R_{e,T,a} from previous studies. Caravello reported a standard error of mean at 0.004 kP m²/W, which is greater than the differences in R_{e,T,a} value among the studies.

Table VIII: R_{e,T,a} Values for Work Clothes and Tyvek

	Work Clothes (kPa m²/W)	Tyvek (kPa m²/W)	Ensemble
Pease	0.011	0.015	Tyvek 1422A
Barker	0.013	0.016	Tyvek 1422A
Caravello	0.013	0.015	Tyvek 1424

The apparent total evaporative resistance for the DuPont prototype ensemble was 0.013 m²kPa/W. This value places the prototype ensemble in between the baseline work clothes (0.011 m²kPa/W) and the Tyvek ensembles (0.015 m²kPa/W). Statistical analysis indicated that the R_{e,T,a} for prototype ensemble was not different from work clothes but was different from Tyvek. This suggests that the DuPont prototype performs closely to work clothes with a slightly higher level of stress.

Progressive and Steady State Protocol

The apparent total evaporative resistance for work clothes using the progressive protocol was 0.011 m²kPa/W. The apparent total evaporative resistance for work clothes using the steady state protocol was 0.012 m²kPa/W and there was no difference between protocols. The difference in R_{e,T,a} between the progressive and steady state protocol was much less than Caravello’s reported standard error of mean (0.004 kP m²/W).

Chapter Six

Conclusion

The results indicate that the unacclimatized participants responded as if acclimatized, which is not easily explained but perhaps due to their daily exercise activities in Central Florida.

Using cotton work clothes as a baseline, the CAF was 1.8 °C-WBGT for the Tyvek® 1422A ensemble, which was similar to previous found values. The CAF for the DuPont prototype ensemble was 0.5 °C-WBGT. The $R_{e,T,a}$ was 0.0110 m²kPa/W for work clothes, 0.0151 m²kPa/W for Tyvek® 1422A and 0.0113 for the prototype ensemble. The prototype had an intermediate contribution to heat stress, which was closer to work clothes than Tyvek® 1422A.

There was no significant difference in apparent total evaporative resistance between the progressive and steady state protocol. In the vicinity of the critical environment, the steady state protocol yielded results similar to the progressive protocol and could be an alternative means of assessing evaporative resistance.

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