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Apparent Total Evaporative Resistance for Clothing Ensembles at High Heat Stress Levels

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Apparent Total Evaporative Resistance Values for Clothing Ensembles

At High Heat Stress Levels

by

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LIST OF ABBREVIATIONS

A_D – Dubois Surface Area
ACGIH – American Conference of Governmental Industrial Hygienists
ANOVA – Analysis of Variance
ASTM – American Society for Testing and Materials

C – Compensable Stage of Heat Stress
C_{res} – Respiratory Convective Heat Flow
CC – Cotton Coveralls
CFI – Correction Factor for Insulation

DH – Dry-Heat Loss

E_{res} – Respiratory Evaporative Heat Flow

H_{net} – Net Heat Gain
HSD – Honestly Significantly Different

I_{clo} - Total Intrinsic Clothing Insulation
I_T – Total Insulation
$I_{T,r}$ – Total Resultant Insulation
$I_{T,stat}$ – Total Static Insulation
ISO – International Organization for Standardization

M – Metabolic Rate

OSHA – Occupational Safety and Health Administration

P_a – Ambient Water Vapor Pressure
P_{sk} – Skin Water Vapor Pressure
$R_{e,T}$ – Total Evaporative Resistance
$R_{e,T,a}$ – Apparent Total Evaporative Resistance
$R_{e,T,stat}$ – Static Total Evaporative Resistance
RH – Relative Humidity

S – Body Heat Storage Rate
SD – Standard Deviation

T_{db} – Ambient Air Temperature

T_{exp} – Expired Air Temperature
T_g – Globe Temperature
T_{pwb} – Psychrometric Wet Bulb
T_{re} – Body Core (Rectal) Temperature
T_{sk} – Skin Temperature
TLV® – Threshold Limit Value

v – Air Speed
V_{O2} – Oxygen Consumption
V_T – Ventilation Index
V_W – Walking Speed

w – Walking Speed or Speed of Treadmill
W – Watts (Effective Mechanical Power)
W_{ext} – External Work
WC – Work Clothes

ΔP – Pressure Gradient ($P_{sk} - P_a$)
ΔT – Temperature Gradient ($T_{db} - T_{sk}$)

ABSTRACT

Donning protective clothing for mitigation of hazard from chemical agents poses a problem in the form of heat stress. When choosing protective clothing, many factors must be taken into account including insulative properties and evaporative resistance. This study calculated and compared $R_{e,T,a}$ for three clothing ensembles at levels of heat stress past the level of compensation for heat gain to determine if $R_{e,T,a}$ values varied or remained the same with changes in heat stress level. A three-way mixed model analysis of variance demonstrated significant differences for estimated $R_{e,T,a}$ values among ensembles, heat stress levels and interactions among ensembles and heat stress levels ($p < 0.0001$). A significant interaction between heat stress levels and ensembles was identified ($p<0.05$). The results of the study indicated that $R_{e,T,a}$ values are affected by levels of heat stress such that increasing levels were associated with lower values of $R_{e,T,a}$. The study also helped to illustrate that $R_{e,T,a}$ values are not a constant associated with clothing, walking speed, and air speed.

CHAPTER 1: INTRODUCTION

The occupational setting is often riddled with hazards which are often controlled through the use of personal protective equipment. Said equipment is useful for defense from chemicals or bacteria but often pose a different threat altogether, heat stress. The Occupational Safety and Health Administration estimates that between five and ten million employees are exposed to sufficiently hot environments as to be hazardous to their health each year. Of those exposed approximately 3100 people were forced to take days away from work and 44 were killed due to heat related illnesses in 2006 (Office of Compliance 2009). Exposure to hot environments can be detrimental to health in a number of ways and can ultimately lead to death if untreated. The most harmful effect of heat stress is heat stroke which can cause permanent damage to vital organs. Proper control measures for heat stress can greatly reduce the risk to health from heat stress and manage heat related disorders.

Thermoregulation is an important aspect of the homeostatic process and is qualified as heat storage. Havenith (1999) defines heat storage qualitatively by the following equation:

$$\text{Storage} = \text{Heat Production} - \text{Net Heat Loss} = (\text{metabolic rate} - \text{external work}) - (\text{conduction} + \text{radiation} + \text{convection} + \text{evaporation} + \text{respiration})$$

This is usually referred to as heat balance (assuming storage is equal to 0) and is used to conceptualize the idea of thermoregulation. If a person is capable of eliminating heat faster than they are gaining it the person is said to be in a state of compensable heat stress. On the other hand, if the person is not able to eliminate heat at the level to which they are gaining it they begin to have a rise in core body temperature. This is known as uncompensable heat stress.

There are a number of factors that influence heat stress in the occupational environment; however, this paper will focus on only two: environmental conditions and clothing. The higher the air temperature the less heat the body can lose through convection, conduction, and radiation (Havenith 1999). The human body gains heat from the surroundings when the air temperature rises above 40˚ C and loses heat when it falls beneath 32˚ C. Air temperature also has an effect on evaporative cooling as warmer air has a higher capacity to retain water than cooler air. Moisture content of the air is the other environmental factor of note. The moisture content of air determines if vapor goes from the skin to the air or vice-versa. Only under extreme environmental conditions will vapor ever travel from the air to the surface of the skin as the moisture content in the air at the skin is usually higher. This is perhaps the most important factor as evaporation of sweat is the chief way in which the body cools itself (Havenith 1999).

Clothing is a risk factor that will be discussed and will be the focus of the remainder of this paper. Clothing is a risk factor for heat stress because it acts as a barrier to heat and vapor exchange. This may not be a factor in a cool environment with moderate work, but it poses a more significant problem if the environment is less forgiving. For higher work rates and temperature, the time of exposure becomes an important factor; with higher temperatures and metabolic rates allowing less exposure times.

The three most important factors relating heat stress to clothing are construction, configuration, and the number of layers worn (Havenith 1999). As most clothing materials have a far greater volume of enclosed air compared to the volume of fibers it is shown that thickness has a greater effect on heat and vapor resistance than fiber type. The thickness of the material is the main factor determining thermal insulation as it prevents air from making contact with human skin and impedes heat transfer and evaporative cooling. The best case scenario would be loose fitting, light weight clothing that would allow evaporative-heat exchange which is the primary way in which heat exchange takes place.

Haventih (1999) has outlined the main determinants of heat stress with regard to thermal properties of clothing. These are total insulation (I_T), usually expressed as a moisture permeability index, and total evaporative resistance ($R_{e,T}$). The latter measure is a very important factor in determining the risk of heat stress and various clothing ensembles. $R_{e,T}$ values are expressed in m^2kPaW^{-1} and can be classified as static ($R_{e,T,stat}$) or resultant ($R_{e,T,r}$) (Kenney 1993). The resultant evaporative resistance represents the resistance when workers are in motion or when air movement plays while static evaporative resistance represents only when no movement, air or otherwise, plays a role. Clothing ensembles play a major a role in evaporative resistance as they can limit the amount of air and vapor movement between the skin and the environment. The reason $R_{e,T,r}$ is so useful in determining heat stress conditions is because it looks at all the layers of clothing simultaneously as well as environmental factors and metabolic rate.

Research Question

The following research question is addressed in this thesis: Will estimates of $R_{e,T,a}$ for three different clothing ensembles remain the same independent of five different uncompensable heat stress levels?

CHPATER 2: LITERATURE REVIEW

Heat Exchange

When in a hot environment the body can exchange heat through a number of pathways. These pathways include convection, radiation and evaporation and are the main ways by which the human body cools itself. Clothing inhibits the body's ability to interact with the environment in the way it would naturally and prevents normal heat exchange. The clothing worn to protect humans from chemical hazards prevents the body from properly transferring heat from the surface of the skin to the outside environment. There are two ways in which clothing prohibits the transfer of heat: first it limits dry heat exchange; and second it limits evaporative-heat exchange. When in hot environments evaporation of perspiration off the skin serves as the primary way in which heat and allows the body to maintain thermal equilibrium. Having said this, the required amount of evaporation required to maintain the body at thermal equilibrium can be described mathematically by the following equation:

$$E_{req} = H_{net} + (R+C) - S \qquad \text{Equation (1)}$$

Equation 1 explains the required amount of evaporation (E_{req}) required for the body to be in thermal equilibrium. The evaporation must be equal to the net heat gain due to internal sources (H_{net}) plus heat gained through dry heat exchange (R+C) minus the heat storage rate in the body (Holmer et al. 1999).

$$E = P_{sk} - P_a / R_{e,T} \qquad \text{Equation (2)}$$

Evaporation can also be described in terms of pressure and evaporative resistance. In this case, the ambient water vapor pressure (P_a) is subtracted from the water vapor pressure at the skin then divided by the resistance to evaporation caused by clothing ($R_{e,T}$). These two equations describe how heat is lost through evaporation, which begs the question as to how heat is gained by the human body. Equations 3 & 4 describe the two ways in which heat is gained through internal sources (H_{net}) and through the external environment (R+C). Internal sources of heat gain are metabolic rate (M) less external work (W_{ext}), the storage rate of heat (S), and respiratory exchange rates due to convection (C_{res}) and evaporation (E_{res}) (Caravello et al. 2008; Kenney et al. 1993).

$$H_{net} = M - W_{ext} - S + C_{res} - E_{res} \qquad \text{Equation (3)}$$

The heat gained from the external environment is due to radiation and convection (R+C). This is related to the temperature gradient between the air and the skin (T_{db}-T_{sk}) and the total insulation provided by clothing.

$$R+C = T_{db} - T_{sk} / I_T \qquad \text{Equation (4)}$$

$$(P_{sk} - P_a) / R_{e,T} = H_{net} + (T_{db} - T_{sk}) / I_T \qquad \text{Equation (5)}$$

A progressive heat stress protocol can be used to identify the critical conditions where the maximum heat loss due to evaporative cooling(vapor pressure difference between the environment [P_a] and the skin [P_{sk}] divided by the apparent total evaporative resistance [$R_{e,T,a}$)] is equivalent to the evaporative cooling .(H_{net}) (metabolic rate [M] minus external work [W_{ext}], storage rate [S] plus respiratory exchange through convection [C_{res}] less evaporation [E_{res}]) and dry heat exchange (for non-radiant environments is approximated by the difference between the dry bulb temperature[T_{db}] and the temperature of the skin [T_{sk}] divided by the total insulation [I_T]) (Caravello et al. 2008; Kenney et al. 1993).

Thermal Insulation

Thermal insulation is one of two clothing driven effects, the other being evaporative resistance. Insulation is defined as the resistance to dry heat exchange for any piece of clothing. Dry heat exchange is accomplished through radiation and convection when clothing is worn it provides insulation which inhibits heat loss through these mediums (Barker et al 1999). Clothing with higher thermal insulation characteristically lowers dry heat exchange through convection and radiation creating more heat stress.

Thermal insulation can be measured by three main methods: heated plate, heated copper manikin, and human wear trials. The heat plate method is outlined by the International Standards Organization (ISO) and is a cheap effective way to test many fabrics. The test is performed using a guarded hot plate inside an environmental chamber and attempts to simulate the heat transfer between the skin and the environment. The heated plate method is not the ideal way to determine the insulation properties of fabrics as it has a number of disadvantages. The heated plate does not take into account human sweating or air movement. The heated copper manikin is the second way in which insulative properties of clothing can be tested. The testing methods for the heated manikin are outlined by the American Society for Testing and Materials (ASTM) and by the ISO. The manikin is equipped with a tight covering meant to mimic skin and placed in an environmentally controlled chamber. This allows researchers to monitor and control environmental conditions and collect data efficiently. The positive of using a manikin over a heated plate is that a whole ensemble can be worn by the manikin as opposed to only testing only the fabric. Manikins are effective for the collection of data on clothing ensembles, however, like heated plates they pose a problem when accounting for real life conditions. Although there are some manikins that are designed for movement, the majority are not and, therefore, do not provide an accurate measure of insulation in a person who is moving (Havenith 2008). Finally, human wear trials are used when feasible and provide the most accurate estimation of thermal insulation values. While human trials are the most accurate in terms of estimating insulation they are very costly and require much time to be put in to data collection. An additional problem associated when using human subjects is the variability of thermoregulation among different people (Barker et al 1999).

As should be expected, these three methods give different values of thermal insulation and must be classified based on applicability to real world situations. The most basic measure of insulation is known as total insulation and is denoted as I_T. Total insulation is attained from heated plate and heated copper manikin trials. Total insulation gives an idea of the insulation of the insulation of a material on a static system. ISO 9920 provided a method to make adjustments to the real world. This is known as resultant total insulation and was denoted as $I_{T,r}$. Finally when insulation is inferred from wear trials it gives the most accurate estimation of total insulation and is known as apparent total insulation denoted $I_{T,a}$.

Evaporative Resistance

As previously stated the other main clothing-related effects affecting heat exchange is evaporative resistance. Evaporative resistance can be defined as a resistance to moisture transfer. When moisture accumulates on the skin heat is then transferred to the moisture which evaporates and is moved to the environment. Since sweating is the main way in which the human body is able to cool itself evaporative resistance of clothing is of critical importance when the body is trying to cool itself (Holmer 2008). Clothing has the effect of increasing evaporative resistance as it provides a barrier between the skin and the air. Increased evaporative resistance is associated with higher levels of heat stress and *vice versa.*

There are three ways in which evaporative resistance can be calculated for a garment or fabric (ISO 11092 1993): sweating hot plate, sweating thermal manikin, and human subjects. The sweating heated plate like that used in determination of insulation is placed in an environmentally controlled room where it is covered in a wet cloth to simulate sweating. In a very similar fashion the "skin" of the thermal manikin is wet to allow for evaporative cooling underneath the garment that is to be tested. Ross in a 2005 study showed that a thermal manikin provides a more realistic value than the sweating hot plate in determination of evaporative resistance. Human subject trials provide the most realistic estimation of total evaporative resistance by measuring the water vapor pressure gradient between skin and air and the steady state rate of evaporative heat loss (Holmer and Elnas 1981). The total clothing evaporative resistance can also be defined in terms of the clothing intrinsic evaporative resistance R_{ecl} and the evaporative resistance of the boundary surface air layer R_{ea} (Holmer 2011):

$$R_{et}=R_{ecl} + R_{ea}/f_{cl}$$

where f_{cl} is the clothing area factor.

In the real world evaporative resistance values may be different from those calculated in the lab. Calculating evaporative resistance in the laboratory setting can be done statically ($R_{e,T,stat}$) or dynamically ($R_{e,T,a}$). Statically determined evaporative resistance tends to be higher than values attained dynamically. This is due to the fact that clothing with a higher porosity as well as increased movement and wind speed tend to have antagonistic effects on evaporative resistance (Bernard et al 2010; Parsons et al 1999). Caravello (2008) shows that dynamic methods of data collection yield conditions that are more like real life and, therefore, are preferable to static calculations.

CHAPTER 3: METHODS

Participant selection:

Twelve adults participated in the time-limited heat stress exposures. Table I provides descriptive statistics for age, height, weight, and body surface area by men, women, and combined. Participants provided written informed consent following IRB guidelines. As noted in Table 3.1, two participants (both men) completed only half the assigned trials (seven for one and eight the other); and four subjects repeated trials on some combinations of ensemble and heat stress level. The repeated trials were not intentionally included in the experimental design. Prior to beginning the experimental trials to determine safe exposure time, participants underwent five 120-min acclimatization sessions in dry heat (50˚C, 20% relative humidity [rh]) at the same metabolic rate as the experimental trials ($190 Wm^{-2}$) during which they wore a base ensemble of shorts, underwear, tee-shirt (or sports bra for women), socks, and shoes. There were five clothing ensembles evaluated previously for clothing adjustment factors.(4) Of these five, three represented the range of clothing adjustments for WBGT.

Table 3.1. Physical characteristics of participants (Mean ± Standard Deviation)

	Age (Years)	Height (cm)	Weight (kg)	Body Surface Area (m^2)
Women (n = 4)	28 ± 9	160 ± 7	66 ± 27	1.67 ± 0.33
Men (n = 8)	33 ± 10	181 ± 4	95 ± 10	2.15 ± 0.09
Both (n = 12)	32 ± 10	174 ± 11	85 ± 22	1.99 ± 0.30

Clothing:

The three different clothing ensembles included in the current study were (1) work clothes (135 g m^{-2} [6 oz/yd^2] cotton shirt and 270 g m^{-2} [8 oz/yd^2] cotton pants), (2) water-barrier, vapor-permeable coverall (NexGen LS 417), and (3) vapor-barrier coverall (Tychem QC, polyethylene-coated Tyvek). The limited-use coveralls had a zippered closure in the front and elastic cuffs at the arms and legs, and they did not include a hood. Each of the trial ensembles was worn over the base ensemble.

Protocol:

The design of the study was to include a range of heat stress conditions for which the participants were not expected to reach 120 min. Five heat stress levels were selected starting with a value (L1 in Table II) that was nominally 1◦C-WBGT higher than the critical WBGT for that clothing ensemble at 50% relative humidity based on previous work, and about 7◦C-WBGT above the TLV. From our experience, the L1 level should result in the loss of thermal equilibrium (uncompensable heat stress) for most participants, but not all. That is, it was expected that safe exposure times would be in the vicinity of 100 to 120 min, and the trial period was limited to 120 min. The following levels (L2 through L5) were approximately 1.0, 2.5, 4.5, and 8.0 °C-WBGT greater than the L1 level. These were expected to produce progressively shorter safe exposure times. The 15 combinations of clothing and heat stress level were assigned to participants in random order. Table II gives the number of trials and the actual normalized metabolic rates and WBGTs (mean ± standard deviation) by clothing ensemble and heat stress level. There were 15 combinations of clothing and environment, and each participant was scheduled for trials for each combination in a partially balanced design to minimize the effects of trial order. Each participant walked on a treadmill at a moderate rate of work (target of 190 W/m^2). During trials, participants were allowed to drink water or Gatorade® at will. Core temperature (T_{re}), heart rate and ambient conditions were monitored continuously and recorded every 5 min. Metabolic rate was calculated from oxygen consumption, which was sampled one to three times during the trial at approximately 30-min intervals. The safe exposure time was taken as the time at which the first of the following conditions was satisfied: (1) T_{re} reached 38.5◦C, (2) a sustained heart rate greater than 85% of the age-predicted maximum heart rate (0.85*[220-Age]), or (3) participant wished to stop. The third criterion was included because a participant may experience fatigue or the early symptoms of heat-related disorders prior to reaching a physiological limit. This was also a participant safety requirement.

Table 3.2. Number of Observations, Normalized Metabolic Rate (W m−2), and WBGT (◦C-WBGT) (mean ±standard deviation) at 50% Relative Humidity for Combinations of Clothing Ensemble and Heat Stress Level

Heat Stress Level					
Ensemble					
Work Clothes	L1	L2	L3	L4	L5
N	11	13	13	13	12
M(W m-2)	187±16	183±21	194±24	188±20	190±24
WBGT(˚C)	36.0±0.6	36.8±1.0	38.2±0.7	40.1±0.9	43.8±1.2
NexGen					
N	11	12	10	11	9
M(W m-2)	183±15	188±19	185±18	181±20	188±21
WBGT(˚C)	33.1±0.5	33.9±0.6	36±1.0	37.8±0.9	41.1±0.5
Tychem					
N	10	11	12	12	15
M(W m-2)	180±15	175±17	182±22	180±23	187±22
WBGT(˚C)	29.5±0.4	30.3±1.1	32.0±1.5	33.7±0.6	37.8±1.5

Equipment

The trials were conducted in a controlled climatic chamber. Temperature and humidity were controlled according to protocol and air speed was 0.5 m s^{-1}. Heart rate was monitored using a chest strap heart rate monitor. Core temperature (T_{re}) 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 on a motorized treadmill at a speed and grade set to elicit a target metabolic rate of 190 W m^{-2}. Measurement of oxygen consumption was used to assess metabolic rate. Participants breathed through a two-way valve connected to flexible tubing that was connected to a collection bag. Expired gases were collected for about 2.5 min. The volume of expired air was measured using a dry gas meter. An oxygen analyzer was used to determine oxygen content of expired air. A metabolic rate was recorded for each trial which 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.

Data Extraction

The progressive heat stress protocol permitted the collection of data at, near, or beyond the critical condition for each participant. Environmental and physiological data were extracted at the uncompensible heat stress level defined as a core body temperature of 38.5˚C. A calibration table of the rectal temperature probes was used to adjust the values in a spreadsheet that were closest to the baseline value of 38.5˚C. In some cases this was the last line of data collected, but in others data continued to be collected afterwards. All identified errors were corrected prior to computing $R_{e,T,a}$ values.

Calculation of Clothing Parameters

Environmental and physiological data for each of the 663 combinations were used to estimate $R_{e,T,a}$ values. The following is the process to calculate derived values for each trial based on trial conditions for the participant and environment.

Referring to Kenney et al. (1993), metabolic rate (M), external work (W_{ext}), storage rate (S), and respiratory exchange rate by convection (C_{res}) and evaporation (E_{res}) presented in equation (2) were estimated as follows. M in W m^{-2} was estimated from oxygen consumption (V_{O2}) in liters per minute:

$$M = 350 \cdot V_{O2} / A_D \qquad \text{Equation (6)}$$

The Dubois surface area (A_D) was calculated for each subject as $A_D = 0.202 m_b^{0.425} \cdot H^{0.725}$, where m_b was the mass of the body (kg) and H was the height (m). W_{ext} was calculated (W m^{-2}) in the following manner:

$$W_{ext} = 0.163 m_b \cdot V_W \cdot f_g / A_D \qquad \text{Equation (7)}$$

V_W was the walking velocity in m min^{-1} while f_g was the fractional grade of the treadmill (%). Values for C_{res} (W m^{-2}) and E_{res} (W m^{-2}) were calculated using equations provided in ISO 7933 (2004a). The estimation of C_{res} required that expired air temperature (T_{exp}) be calculated using T_{db} and P_a:

$$T_{exp} = 28.56 + (0.115 \cdot T_{db}) + (0.641 \cdot P_a)$$ Equation (8)

$$C_{res} = 0.001516 \cdot M (T_{exp} - T_{db})$$ Equation (9)

$$E_{res} = 0.00127 \cdot M (59.34 + 0.53 \cdot T_{db} - 11.63 \cdot P_a)$$ Equation (10)

Kenney et al. (1993) recognized that there may be some heat storage represented by a gradual change in T_{re}. To account for this, the rate of change in heat storage can be estimated knowing the specific heat of the body (0.97 W h $^{o}C^{-1}$ kg^{-1}), m_b, and the rate of change of body temperature (ΔT_{re} Δt^{-1}) as an average over the 20 minute period preceding the inflection point. This approach was taken by Barker et al. (1999) with some changes in sign conventions:

$$S = 0.97 m_b \cdot \Delta T_{re} A_D^{-1} \Delta t^{-1}$$ Equation (11)

Total static clothing insulation ($I_{T,stat}$) values were determined according to ASTM F 1291, *Standard Test Method for Measuring the Thermal Insulation of Clothing using a Heated Manikin*, using a fixed environment and adjusting the heat input to achieve thermal equilibrium (ASTM, 2002). In the current study, these values were treated as a fixed value for all ensembles.

The total dynamic clothing insulation ($I_{T,r}$) was estimated according to ISO 9920 (2007) (Equation 32) in two stages. First, the correction factor for insulation (CFI) was calculated according to Havenith and Nilsson (2004) (Equation 4) and ISO 9920 (2007) where v is air speed (0.5 m s^{-1}) and w refers to walking speed or speed of the treadmill (m s^{-1}) for each wear trial. This adjustment for air and body movement was similar to that proposed by Holmer et al. (1999). The equation to estimate the CFI is as follows:

$$CFI = \exp[-0.281(v - 0.15) + 0.044(v - 0.15)^2 - 0.492w + 0.176w^2]$$ Equation (12)

Second, $I_{T,stat}$ and CFI values were multiplied by 0.9 (reduced by 10%) finalizing the estimated $I_{T,r}$ to account for the reduction in insulation due to wetting (Brode et al. 2008):

$$I_{T,r} = CFI \cdot I_{T,stat} \cdot 0.9$$ Equation (13)

$R_{e,T,a}$ values were calculated by rearranging equation (1).

$$R_{e,T,a} = (P_{sk} - P_a) / [H_{net} + (T_{db} - T_{sk}) / I_{T,r}]$$ Equation (14)

Each $I_{T,r}$ value was inserted into equation (11) along with other applicable environmental and physiological data for each combination to estimate the $R_{e,T,a}$. The process was repeated yielding 663 $R_{e,T,a}$ values in all.

Statistical Analysis

JMP® (version 7.1) statistical software (SAS, Cary, North Carolina) was used to analyze data. A mixed model analysis of variance (ANOVA) in combination with Tukey's Honestly Significant Difference (HSD) multiple comparison tests were used to determine where the main differences occurred. To analyze the relationships among ensembles and heat stress stages, a three-way ANOVA was performed in which those factors were fixed effects and the participants were maintained as a random effect. Also evaluated was the interaction between ensembles-heat stress stages. The dependent variable for the statistical test was $R_{e,T,a}$ and significance was established at $\alpha = 0.05$.

CHAPTER 4: RESULTS

Main Effects

A Tukey's HSD multiple comparison test was used to identify differences among ensembles and heat stress levels. Significant differences ($p < 0.05$) were detected between all three clothing ensembles as is evident in Table 4.1. The highest apparent total evaporative resistance was seen in the Tychem QC® ensemble followed by the Nexgen and work clothes.

Table 4.1. Least Squares Mean of Apparent Total Evaporative Resistance (m^2kPa/W) for Three Ensembles

Ensembles	Evaporative Resistance(m^2kPa/W)
WC	0.008
Nexgen	0.011
Tychem	0.019

* significant differences ($p < 0.05$) among all ensembles

The Tukey's HSD showed that there was no significant difference between H1 and H2. There were significant differences ($p < 0.05$) between H1, H2, and the other levels. Estimated $R_{e,T,a}$ values were highest at H1 and lowest at H5 as demonstrated by Table 4.2.

Table 4.2. Least Squares Mean of Apparent Total Evaporative Resistance (m^2kPa/W) for Five Heat Stress Stages

Heat Stress Stage	Evaporative Resistance(m^2kPa/W)	Statistical Difference*
H1	0.016	A
H2	0.015	A
H3	0.013	B
H4	0.011	C
H5	0.007	D

*Similar letters denote no significant differences ($p < 0.05$)

Interactions

The estimated $R_{e,T,a}$ values for each clothing ensemble at different heat stress levels are shown in Table 4.4, and $R_{e,T,a}$ values for every ensemble at the five heat stress levels are illustrated in Figure 4.1. The results from Tukey's HSD test revealed that $R_{e,T,a}$ values for the Tychem QC® ensemble were statistically different ($p < 0.05$) from $R_{e,T,a}$ estimates for all other ensembles at different heat stress levels.

Table 4.3. Least Squares Mean of Apparent Total Evaporative Resistance (m^2kPa/W) for Three Ensembles at Five Heat Stress Levels

		Ensembles		
		WC	Nexgen	Tychem
Heat Stress Level	H1	0.010	0.013	0.024
	H2	0.009	0.013	0.023
	H3	0.008	0.011	0.020
	H4	0.007	0.010	0.017
	H5	0.044	0.006	0.012

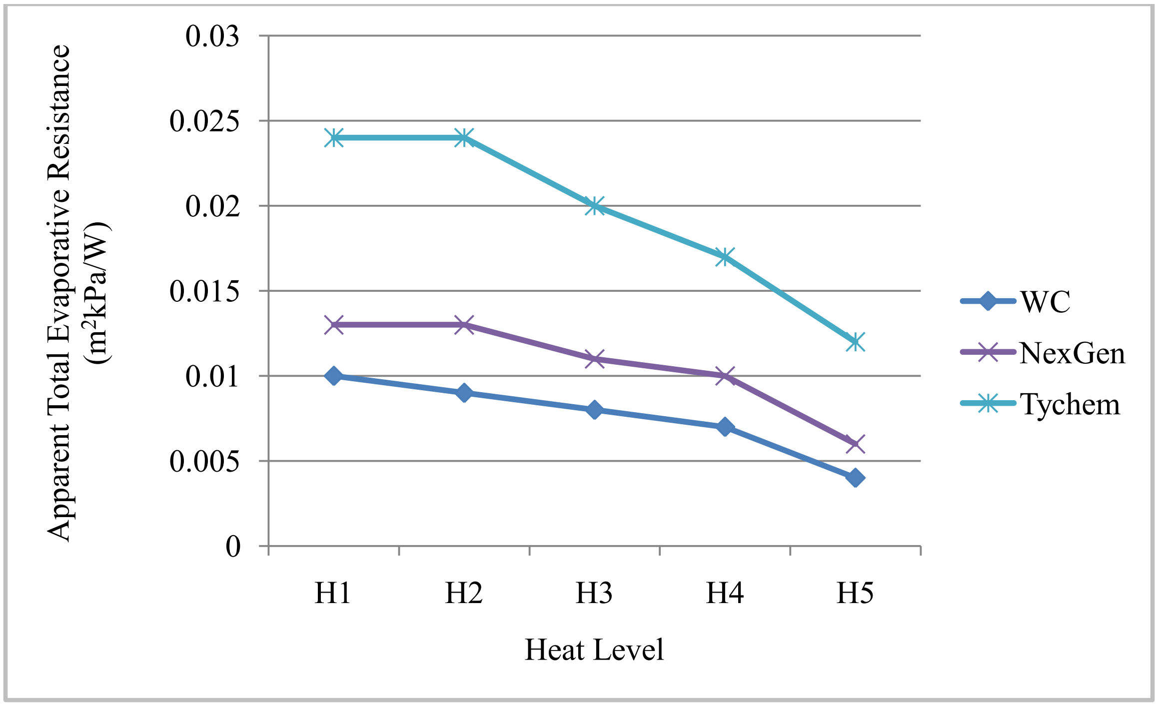

Figure 4.1 Least Squares Mean of Apparent Total Evaporative Resistance for Three Ensembles at Five Heat Stress Levels

CHAPTER 5: DISCUSSION

Analysis of Results:

Apparent total evaporative resistance is the best estimate for the evaporative resistance of clothing being worn by people in hot environments. In this case, metabolic rate and relative humidity were controlled and the effect of high heat stress levels on apparent total evaporative resistance were studied. Based on previous research using the same clothing ensembles (Caravello et al 2008 and Dooris 2011) it was anticipated that the evaporative resistance would vary. Dooris (2011) found that for work clothes (WC) the apparent total evaporative resistance was 0.014 m^2kPa/W; for NexGen® LS 417 it was 0.019 m^2kPa/W; and for Tychem QC® evaporative resistance was 0.034 m^2kPa/W. The values presented in Table 4.4 for heat stress level 1 were noticeably lower than the values presented by Dooris and Caravello et al. However, as is shown in the Dooris study with increasing heat stress stage a decrease in apparent total evaporative resistance was seen.

Statistical differences between the heat stress levels and the interaction between the heat stress level and the ensemble were not foreseen. In order to better understand the differences in apparent total evaporative resistance between heat stress levels and the interaction the factors that affect evaporative resistance need to be looked. First, evaporative resistance needs to be defined in terms of pressure gradients and the relationship it has with temperature gradient. To do this equation 14 will be used.

$$R_{e,T,a} = (P_{sk} - P_a) / [H_{net} + (T_{db} - T_{sk}) / I_{T,r}] \quad \text{Equation (14)}$$

Net heat gain (H_{net}) and total resultant insulation ($I_{T,r}$) remain the same throughout the trials with increasing heat stress. Therefore, one must look at the pressure gradients and temperature gradients to better understand how they affect apparent total evaporative resistance. Increases in temperature gradients ($T_{db} – T_{sk}$) and decreases in vapor pressure gradients ($P_{sk} – P_a$) will lead to lower $R_{e,T,a}$ values.

To better understand these study results all the determining factors in equation 11 were calculated for two different clothing ensembles and the five heat stress levels in Table 5.1. Work clothes was chosen as a baseline as it was similar to NexGen in some ways and Tychem QC® was chosen as it was different from the other ensembles in every condition.

Table 5.1. Apparent Total Evaporative Resistance Values, Temperature and Pressure Gradients, and Net Heat Gain Plus Dry-Heat Loss Values for Two Ensembles at Five Heat Stress Levels

Ensembles	WC					Tychem				
Heat Stress Levels	H1	H2	H3	H4	H5	H1	H2	H3	H4	H5
$R_{e,T,a}$ (m^2kPa/W)	0.01	0.009	0.008	0.007	0.004	0.024	0.023	0.02	0.017	0.012
ΔP (kPa)	2.36	2.07	2.13	1.81	1.32	3.58	3.62	3.49	3.18	2.61
ΔT (^{o}C)	0.409	0.569	0.567	0.853	0.841	0.424	0.483	0.673	0.788	0.781
DH* (W m^{-1})	60.2	64.4	77.6	92.1	117.9	-20.3	-7.2	5.4	21.2	56.5
H_{net} + DH* (W m^{-1})	235	238	258	265	299	148	155	174	189	230

* DH = ($T_{db} – T_{sk}$) / $I_{T,r}$

The relationships among $R_{e,T,a}$ values, vapor pressure gradients, and H_{net} plus DH for WC and Tychem QC® ensembles at three different RH levels were illustrated in Figure 5.1.

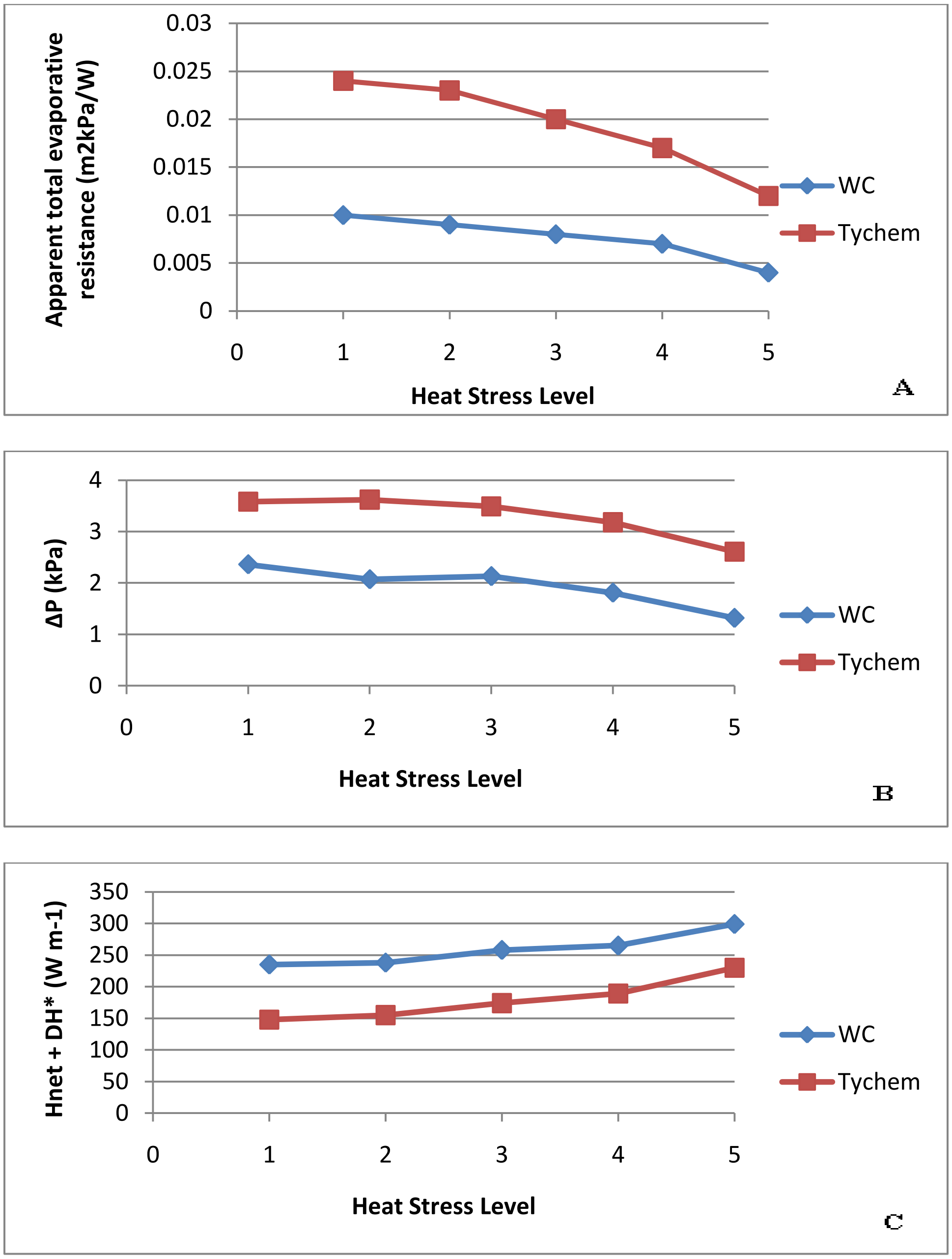

Figure 5.1. Least Squares Mean of Apparent Total Evaporative Resistances (A), Average Pressure Differences (B), and Net Heat Gain Plus Dry-Heat Loss (C) for Two Ensembles at Five Heat Stress Levels.

Figure 5.1 helps illustrate the decrease in the numerator of Equation 11 (ΔP) and the increase in the denominator (H_{net} + DH). This helps to explain the decrease seen in

$R_{e,T,a}$ as the decreasing numerator and increasing denominator would lead to smaller values. These trends also help to understand the interaction such that the proportional drop in $R_{e,T,a}$ was greater with a higher overall evaporative resistance demonstrated by A in Figure 5.1 where $R_{e,T,a}$ for Tychem® decreases with a higher slope than work clothes.

Table 5.2 Percent Difference Between Heat Stress Levels 1 and 5 for Vapor Pressure Gradient, Dry Heat Exchange + Net Heat Gain, and Apparent Total Evaporative Resistance

	Ensembles		
	WC	NexGen	Tychem
% changeΔP	-44%	-36%	-27%
% changeH_{net}+DH	+27%	+22%	+56%
% change $R_{e,T,a}$	-60%	-52%	-54%

The overall changes in $R_{e,T,a}$ in Table 5.1 were highest at heat stage 5 and lowest at heat stage 1, with about a 55% change. But the drivers for the changes varied by ensemble from work clothes to vapor barrier, where there was a decreasing change in vapor pressure gradient and increasing change in the denominator (H_{net} + DH). This helps illustrate why $R_{e,T,a}$ decreased as heat stress level increased as in equation 14 the decreasing pressure gradient in the numerator and the increasing H_{net} +DH in the denominator would lead to a decrease in $R_{e,T,a}$.

Conclusion

The results of this study showed that $R_{e,T,a}$ values are affected by high heat stress levels and the further from the compensable heat stress level $R_{e,T,a}$ continues to decline.

The study also helps illustrate that $R_{e,T,a}$ is not a constant associated with clothing, walking speed and air speed.

REFERENCES

American Society for Testing and Methods. (2005). *Standard method for measuring the evaporative resistance of clothing using a sweating manikin* (ASTM F1291-05). West Conshohocken, Pennsylvania: ASTM International.

Barker, D.W., Kini, S., & Bernard, T.E. (1999). Thermal characteristics of clothing ensembles for use in heat stress analysis. *American Industrial Hygiene Association Journal, 60*(1), 32-37.

Belding, H.S., & Kamon, E. (1973). Evaporative coefficients for prediction of safe limits in prolonged exposures to work under hot conditions. *Federal Proceedings*, *32*(5), 1598-1601.

Bernard, T.E., Ashley, C., Trentacosta, J., Kapur, V., & Tew, S. (2010). Critical heat stress evaluation of clothing ensembles with different levels of porosity. *Ergonomics, 53*(8), 1048-1058.

Bernard, T.E., & Ashley, C.D. (2009). Short-term heat stress exposure limits based on wet bulb globe temperature adjusted for clothing and metabolic rate. *Journal of Occupational and Environmental Hygiene, 6*(10), 632-638.

Bernard, T.E., Luecke, C.L., Schwartz, S.W., Kirkland, K.S., & Ashley, C.D. (2005). WBGT clothing adjustments for four clothing ensembles under three relative humidity levels. *Journal of Occupational and Environmental Hygiene, 2*(5), 251-256.

Bernard, T.E. (1999). Heat stress and protective clothing: An emerging approach from the United States. *Annals of Occupational Hygiene, 43*(5), 321-327.

Bouskill, L.M., Havenith, G., Kuklane, K., Parsons, K.C., & Withey, W.R. (2002). Relationship between clothing ventilation and thermal insulation. *American Industrial Hygiene Association Journal, 63*, 262-268.

Caravello, V., McCullough, E.A., Ashley, C.D., & Bernard, T.E. (2008). Apparent evaporative resistance at critical conditions for five clothing ensembles. *European Journal of Applied Physiology*, *104*(2), 361-367.

Dooris, Matthew. (2011). *Apparent Total Evaporative Resistance Values from Human Trials Over a Range of Heat Stress Levels* . (Master's Thesis).

Frye, A.J., & Kamon, E. (1981). Responses to dry heat of men and women with similar aerobic capacities. *Journal of Applied Physiology, 50*(1), 65-70.

Gonzalez, N.W., Bernard, T.E., Carroll, N.L., Bryner, M.A., & Zeigler, J.P. (2006). Maximum sustainable work rate for five protective clothing ensembles with respect to moisture vapor transmission rate and air permeability. *Journal of Occupational and Environmental Hygiene, 3*(2), 80-86.

Grace, Brian. (2011). *Apparent Total Evaporative Resistance values from Human Trials Over a Range of Metabolic and Heat Stress Levels* . (Master's Thesis).

Havenith, G., Zhang, P., Hatcher, K., & Daanen, H. (2010). Comparison of two tracer gas dilution methods for the determination of clothing ventilation and of vapour resistance. *Ergonomic, 53*(4), 548-558.

Havenith, G., Richards, M.G., Wang, X., Brode, P., Candas, V., den Hartog, E., et al. (2008). Apparent latent heat of evaporation from clothing: Attenuation and "heat pipe" effects. *Journal of Applied Physiology*, *104*, 142-149.

Havenith, G., & Nilsson, H. (2004). Correction of clothing insulation for movement and wind effects, a meta-analysis. *European Journal of Applied Physiology, 92*(6), 636-640.

Havenith, G. (1999). Heat balance when wearing protective clothing. *The Annals of Occupational Hygiene*, *43*(5), 289-296.

Havenith, G., Heus, R., & Lotens, W.A. (1990). Resultant clothing insulation: A function of body movement, posture, wind, clothing fit and ensemble thickness. *Ergonomics*, *33*(1), 67-84.

Holmer, I. (2006). Protective clothing in hot environments. *Industrial Health, 44*, 404-413.

Holmer, I., Nilsson, H., Havenith, G., & Parsons, K. (1999). Clothing convective heat exchange–Proposal for improved prediction in standards and models. *Annals of Occupational Hygiene*, *43*(5), 329-337.

Huang, J., & Chen, Y. (2011). Effect of environmental parameters on water vapor transfer of fabrics. *The Journal of the Textile Institute, 102*(1), 50-56.

International Organization for Standardization 9920. (2007). *Ergonomics of the thermal environment: Estimation of the thermal insulation and water vapour resistance of a clothing ensemble*. Geneva, Switzerland: International Organization for Standardization.

International Organization for Standardization 7933. (2004a). *Ergonomics of the thermal environment: Analytical determination and interpretation of heat stress using calculation of the predicted heat strain*. Geneva, Switzerland: International Organization for Standardization.

International Organization for Standardization 8996. (2004b). *Ergonomics – Determination of metabolic heat production*. Geneva, Switzerland: International Organization for Standardization.

International Organization for Standardization 15831. (2004c). *Clothing – Physiological effects – Measurement of thermal insulation by means of a thermal manikin*. Geneva, Switzerland: International Organization for Standardization.

International Organization for Standardization 11092. (1993). *Textiles – Physiological effects – Measurement of thermal and water-vapour resistance under steady-state conditions (sweating guarded – hotplate test)*. ISO. Geneva, Switzerland.

Kenney, W.L., Mikita, D.J., Havenith, G., Puhl, S.M., & Crosby, P. (1993). Simultaneous derivation of clothing-specific heat exchange coefficients. *Medicine & Science in Sports & Exercise*, *25*(2), 283-289.

Levine, L., Sawka, M.N., & Gonzalez, R.R. (1998). Evaluation of clothing systems to determine heat strain. *American Industrial Hygiene Association Journal, 59*(8), 557-562.

Lind, A.R. (1963). A physiological criterion for setting thermal environmental limits for everyday work. *Journal of Applied Physiology, 18*, 51-56.

Office of Compliance. (2009). *Heat stress: Don't let the heat get you down*. Washington, D.C.: Congressional Accountability Office of Compliance.