

## **Making Heat Stress Assessment Relevant Again**

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The mention of product names for the clothing does not represent an endorsement. It is necessary for a precise description of the fabric and construction.

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## **Abstract**

Occupational heat stress occurs in hot work environments, during heavy work, while wearing protective clothing, or from any combination of these. The exposures may be routine for those in hot industries like metal and glass manufacturing to intermittent like emergency response. Workers frequently experience heat exhaustion and are at risk for exertional heat stroke. They are also more likely to make mistakes and suffer injuries.

The usual method to assess heat stress is to report the environmental conditions in an index called wet bulb globe temperature (WBGT). An occupational exposure limit can be set as an upper limit on WBGT, where the limit is modified for different work demands. The limit assumes continuous exposures over the day.

This research addressed two shortcomings of this approach. First, the occupational exposure limits were developed with work clothes in mind. This means that non-woven protective clothing is not accounted for; leaving it to the professional judgment of the health professional. Second, many heat stress exposures are not continuous and an open question is how long should a person work above the occupational exposure limit. A third aim of the research was to examine the resistance of the clothing to cooling by the evaporation of sweat.

The evaluation of clothing for use in the standard heat stress evaluation method was very productive. Factors were recommended for four common clothing ensembles that could be added to the ambient WBGT to reflect the added heat stress of the clothing. The adjustment applies to a wide range of work demands and environments. The recommended adjustment factor for cloth coveralls is 0 (this same as work clothes); for a polyethylene-based particle-barrier coveralls, 0.5 °C; for a water-barrier, vapor-permeable film laminate coveralls, 2 °C; and for a limited-use vapor-barrier coverall, 10 °C. Because a vapor-barrier fabric behaves much differently, the recommendation was made for a value that would be protective over a wide range of humidities.

Based on trials with time-limited heat stress exposures, a curve relating WBGT to safe exposure time was generated that is protective of 95% of the people. The clothing adjustment factors account for the added heat stress in the time-limited exposures as well. In addition, the research allowed for an adjustment to the equivalent WBGT for different work demands. The curve is most applicable to safe exposure times between 20 and 90 minutes. Above 90 minutes, the occupational exposure limit for continuous work would apply. There is a tendency to be overly protective above 45 minutes and further investigations into the data from this research combined with other research is likely to compensate for this.

Quantifying the resistance to cooling by sweat evaporation can distinguish among different fabrics and clothing construction. This is useful for the comparison of clothing systems. An unexpected new finding was that the resistance increases with the decrease in ambient humidity. This means that the predicted cooling is less the observed cooling. The implications for this require further study.

## Significant Findings

### *Clothing Adjustment Factors*

The essence of the Clothing Adjustment Factor is to add a value to the ambient WBGT that represents the added heat stress due to the clothing. The following are the recommended Clothing Adjustment Factors for the ensembles that were examined in the current study. These values account well for the effects of humidity and different metabolic rates.

Ensemble	CAF [°C]
Work Clothes (Reference)	0
Cloth Coveralls	0
Limited-Use Particle Barrier Coveralls (specifically Tyvek 1427) Note: From previous research, an SMS fabric is likely to have a -1 °C CAF	0.5
Limited-Use Water-Barrier, Vapor-Permeable Coveralls (specifically NexGen) Note: A wide variation in CAFs are expected for the films and laminates that provide the barrier properties.	2
Limited-Use Vapor-Barrier Coveralls (specifically Tychem QC) Note: The actual vapor-barrier fabric is not critical in establishing the CAF.	10

### *Safe Exposure Time*

Often a heat stress exposure is greater than the occupational exposure limit for continuous exposures. The research effort began to address the determination of a safe exposure time. The determination of time is based on a three step process. The first step is to assign a WBGT adjustment for the clothing. This is the Clothing Adjustment Factor from the above table or elsewhere. The second step is to adjust the WBGT to account for the metabolic rate. Combining the first and second steps, the following equation can be used generate an equivalent WBGT starting with the ambient WBGT.

$$WBGT_{\text{equiv [C]}} = WBGT_{\text{amb [°C]}} + CAF [\text{°C}] + 0.017 (M_{\text{[W]}} - 380)$$

Then the third step is to compute the safe exposure time.

$$t_{\text{safe exp [min]}} = 8.23 \times 10^7 / WBGT_{\text{equiv}}^{4.08} [\text{°C}]$$

### *Total Evaporative Resistance*

The determination of total evaporative resistance was able to distinguish among the different ensembles. The study did find that total evaporative resistance depends on the water vapor pressure gradient between the skin and the air. This dependency was not observed before. The implications for using the information in rational heat stress models is open for discussion.

## **Translation of Findings**

### *Clothing Adjustment Factors*

The major contribution of this research effort was the establishment of Clothing Adjustment Factors as a viable approach to include the effects of protective clothing on heat stress. The results are robust to a range of environmental humidities and metabolic rates, which makes them broadly applicable. The only difficulty is the application to vapor-barrier clothing. Because WBGT does not map the heat stress for vapor-barrier very well, the adjustment must rely on a protective end of the range that depends on the level of humidity.

The Clothing Adjustment Factors are ready for immediate adoption by users. The basic paper has undergone peer review and is being presented to the ACGIH for adoption as a Notice of Intended Change in 2005.

### *Safe Exposure Time*

Guidance for a safe exposure time has been available to US Navy shipboard personnel for 30 years. Other guidance from the Electric Power Research Institute and through the use of work/rest cycles following established exposure limits have been used by others. The most widely used approach is a rational heat stress assessment that considers the sweating requirements and heat storage. The method described in the current report offers an empirical method based on the well-established WBGT and adapted to the Clothing Adjustment Factors. This expands the range of the Navy guidance and applies to a less fit group of workers. While the described method is a good start, it is likely to undergo some fine tuning as the paper goes through the peer review process.

### *Total Evaporative Resistance*

The determination of total evaporative resistance is a robust way to compare different clothing ensembles in terms of fabrics and configuration. In this way, it can provide insight to how protective clothing might contribute to heat stress. The measured values can be used to adapted rational models of heat stress to non-woven clothing. Because the total evaporative resistance appears to depend on the water vapor pressure gradient between the skin and the environment, this phenomenon requires more analysis to articulate the implications for heat stress analysis.

## Introduction

The degree of heat stress in a workplace is reflected in the combination of environmental conditions, work demands and clothing requirements. From the early 1970s, the evaluation of heat stress has been based on an environmental exposure index modulated by the work demands of the task in question. Two fundamental assumptions have been built into the thinking: (1) the exposures are continuous for eight hours and (2) the clothing ensemble is ordinary work clothes.

Specifically, the wet bulb globe temperature (WBGT) index serves as the marker for environmental conditions. Lind proposed an Upper Limit of the Prescriptive Zone (ULPZ) to describe the environmental conditions at a given metabolic rate below which thermal equilibrium could be maintained with no change in core temperature.<sup>1</sup> This is the work-driven zone, and represents fully compensable heat stress. Above the ULPZ is the environmentally-driven zone, where core temperatures are less stable or not maintained at all. When core temperature cannot be maintained, the heat stress is considered uncompensable.

A panel of experts for the World Health Organization recommended a core temperature limit of 38°C for chronic exposures to heat stress.<sup>2</sup> That is, they felt that workers could safely tolerate nominal elevations of 1°C above normal body temperature for prolonged periods of time, which can only occur during fully compensated heat stress. It should be noted that this same panel believed that transient elevations to 39°C could be well-tolerated during uncompensated heat stress exposures. These core temperature thresholds are supported by US Army studies.<sup>3</sup>

Experts at the National Institute for Occupational Safety and Health (NIOSH) observed that body core temperature was not only well-controlled below Lind's upper limit of the prescriptive zone, but they were below 38°C. By keeping the heat stress exposures in the work-driven zone, there was no apparent risk to workers. Through studies to determine the upper limit of the prescriptive zone for a large number of people, the NIOSH experts were able to support a protective limit that has become the Recommended Exposure Limit (REL) in the revised criteria document of 1986.<sup>4</sup> (The American Conference of Governmental Industrial Hygienists [ACGIH] adopted a TLV® for heat stress in 1974, which was actually the limit first envisioned by the NIOSH experts.) The International Organization for Standardization (ISO) has also adopted a WBGT-based threshold limit,<sup>5</sup> which is fundamentally the same as the TLV and REL.

While the WBGT-based thresholds for chronic (fully compensable) exposure typified by the ACGIH TLV have served the occupational health and safety community well over the past 30 years, several short-comings are apparent. Two important ones are (1) the use of clothing ensembles that are not necessarily represented by ordinary work clothes and (2) frequent exposure scenarios better described as uncompensable heat stress. To adjust the approach to heat stress evaluation, the ISO<sup>6</sup> and the ACGIH Physical Agents Committee<sup>7</sup> are promoting a process that uses a WBGT-based limit as a screening tool. If the exposures exceed the initial screen, then a rational method of heat stress analysis and/or physiological monitoring may be appropriate. A rational method is one in which the biophysics of heat exchange are combined into a model for heat stress analysis. The added information provides a better prediction of heat stress and an

understanding of the major contributors. Physiological monitoring acknowledges an indeterminate or high level of heat stress, and assesses protection through limits on physiological strain. Physiological monitoring is reactive in nature and does not provide information on the contributors to heat stress.

The original heat stress limits for fully compensable exposures were for people wearing ordinary work clothes, which were a 4 oz/yd<sup>2</sup> cotton long sleeve shirt and 8 oz/yd<sup>2</sup> cotton pants. This was a typical work uniform. There is no apparent reason to believe that polyester and cotton blend fabrics of similar weight change the clothing effects. Many work places use cloth coveralls in lieu of a shirt and pants. Work around particulate contaminants such as asbestos, lead and radionuclides usually require particle barrier clothing with various degrees of hold-out properties. Some liquid contaminants can be sufficiently stopped by vapor-transmitting materials and others require vapor-barriers. While there is a possibility for some of the fabrics to reduce the level of heat stress, most of the fabrics along with the usual construction and use of the ensembles increase the level of heat stress. A problem arises when an occupational exposure decision must be made for employees wearing a protective clothing ensemble. Said another way, there is little information on how different clothing affects the upper limit of the prescriptive zone, below which the heat stress is fully compensable. The state-of-the-art is represented by clothing adjustment factors for a limited number of ensembles including work clothes as the baseline, woven coveralls, double coveralls, and a vapor-transmitting film. The value for the coveralls may overestimate the heat stress and various vapor-transmitting films have widely different values.<sup>8</sup>

Because many uncompensated heat stress exposures may be safe for a limited period of time, more information on safe time limits is needed for their use in occupational safety and health practice. For instance, the US Navy physiological exposure limits (PHELs) are WBGT-based time limits for uncompensable heat stress while wearing standard clothing.<sup>9</sup> It may be possible that clothing adjustment factors can account for clothing differences in PHEL-like exposure guidelines. Most rational models of heat exchange for use in occupational settings do not have coefficients for non-woven clothing. The development of better coefficients will explain the role of clothing during time-limited heat stress exposures.

The first goal of the study was to determine WBGT adjustment factors for each ensemble to provide a literal update of the current assessment method to account for protective clothing. The study also considered interactions of clothing with the environment and the metabolic rate.

The second goal of the study was to provide a means of accounting for clothing in heat exchange modeling to estimate safe exposure times. The method improves on bench and mannequin tests by using active people in environments with elevated temperatures and humidities. This accounts for clothing pumping effects and wet clothing and for non-woven clothing.

The third goal of the study was develop an empirical model of less complexity than rational models for practical application in evaluating time-limited heat stress exposures.

## Literature Review

### *Clothing Adjustment Factors*

The evaluation of heat stress routinely centers on the TLV line, which is a relationship between environmental conditions and work demands below which most healthy workers can maintain thermal equilibrium. In this way, body core temperature can be maintained and the heat exposure is controlled. The TLV for acclimated workers was developed with the assumption that ordinary work clothes would be worn. To account for the effects of other clothing ensembles, the idea for WBGT adjustment factors was promoted by several investigators.<sup>10-12</sup> This idea was first considered by the Physical Agents Committee in 1990 and is reflected in the current TLV for heat stress, with adjustment factors for three other clothing ensembles. These adjustment factors were based on professional judgment and a survey of actual practices.

A laboratory method to assess the upper limit of the prescriptive zone has been refined by Kenney<sup>13</sup> from the work of Belding and Kamon.<sup>14,15</sup> It is a progressive heat exposure method that has been used to determine the effects of clothing on heat stress. For a constant rate of work, a trial began in a relatively cool environment until a physiological steady-state was achieved. Then the environmental contribution to heat stress was slowly increased while core temperature was monitored. When core temperature began to increase with changes in the environment, the person was entering the environmentally-driven zone. This point is analogous to the upper limit of the prescriptive zone. The WBGT of the environment at this transition point is called the critical WBGT and provides a point for comparison.

Kenney<sup>12</sup> suggested safe exposure limits based on the lower limit (two standard deviations from the mean) for the range of critical WBGTs he observed for several clothing ensembles. To develop clothing adjustment factors, the thought process of Kenney can be extended as suggested by O'Connor and Bernard.<sup>8</sup> First, the average of the critical WBGTs was taken to represent a clothing ensemble. This removed the uncertainty inherent in an estimate of variance with a small sample size. Then, the average value for an ensemble of interest was compared to the average value for ordinary cotton work clothes. In this way, the values were relative to the same ensemble used to establish the TLV. Remember that the TLV already accounted for the least tolerant workers.

Kenney<sup>16</sup> compared work clothes to cloth coveralls with hood, double cloth coveralls with hood, and limited use vapor-barrier coveralls over coveralls with hood. The coveralls were a heavy cotton used for anti-contamination protection in nuclear power plants and the vapor barrier was a polyethylene film on Tyvek® fabric. While his proposed basis of comparison was a WBGT that was two standard deviations from the mean, the difference from mean values was reported here to follow the approach of O'Connor and Bernard.<sup>8</sup> Using Kenney's mean work clothes values as a reference (reported in Kenney et al.<sup>7</sup>, the resulting WBGT adjustment factors were 3 °C for cloth coveralls, 7 °C for double cloth coveralls, and 19 °C for a limited-use vapor-barrier ensemble over coveralls. Data from Kenney<sup>16</sup> (based on the difference between two standard deviations from the mean) would suggest a value around 9 to 11 °C for the

vapor-barrier ensemble. This lower difference was similar to reports by Paull and Rosenthal<sup>18</sup> and Reneau and Bishop.<sup>19</sup>

O'Connor and Bernard<sup>8</sup> have looked at the critical WBGTs for 19 ensembles studied at the University of South Florida over a five year period. These represented both commercially-available and prototype fabrics. The critical WBGT was found for a dry (20% relative humidity) and humid environment (70% rh) for 13 of the ensembles and for an intermediate humidity (50% rh) for 8 ensembles, where work clothes and another ensemble were tested in both sets of environments. The clothing adjustment factor (CAF) was basically the average critical WBGT for the test ensemble minus the average for the reference work clothes ensemble.

Table 1 is a summary of their results for the 13 commercially-available ensembles, where CAF is the clothing adjustment factor. (The parameter  $R_{e-t}$ , is associated with a rational model for evaluation discussed below.) Other ensembles are included to complete the picture of what may be known so far.

While the USF studies found significant differences among ensembles and values that may help perform exposure assessments, there were some weaknesses in the results. First, the reference ensemble (work clothes) had only four subjects and it was not repeated across studies. This means that there was little control over inter-subject differences. If there was a bias in this subject population over the others, then there was a systematic bias in the reported CAFs. The small number of subjects in each study makes comparisons between studies difficult. Second, the ensembles were selected to meet the comparison needs of the research sponsors. For instance, the FR ensembles were selected to consider candidate ensembles for a particular company, and the non-woven, limited-use particle-barriers were for two different studies that were comparing prototypes to a market niche. Clearly missing were woven coveralls (e.g., FR cotton, Nomex®, and cotton) and vapor-barrier coveralls. Among the prototype garments, there were several vapor-transmitting films that had much different CAFs, suggesting that these do not easily fit a generic category.

Table 1: Values of total evaporative resistance ( $R_{e-t}$ ) and WBGT clothing adjustment factor (CAF) for ensembles studied at the University of South Florida, except as noted as estimated or from the literature.

Ensemble	$R_{e-t}$ [kPa m <sup>2</sup> /W]	CAF [°C-WBGT]
Work Clothes w/ Undershirt	0.0131	0.0
Tyvek® 1422A Coveralls with Hood	0.0164	1.8
Spun-bonded, melt-blown polypropylene Coveralls w/ Hood	0.0109	-1.1
Amoco Microporous Film Coveralls with Hood	0.0176	2.6
Limited Use Vapor-barrier Coveralls with Hood (literature)	N/A	8
Encapsulating Suit (literature)	N/A	11
ProTech 2000 Coveralls with Hood (estimated)	N/A	0
ProTech 2000 Coveralls with Hood and Scrub Suit	0.0196	3.0
Cloth Coveralls with Hat (CAF estimated)	0.0176	3.5
Cloth Coveralls with Hood and Scrub Suit (CAF estimated)	0.0256	4.5
Zirpo® Wool Shirt & FR8 Denim Pants	0.0141	0.5
FR9 Cotton Shirt and Pants (no undershirt)	0.0144	0.8
FR9 with Undershirt	0.0156	1.3
FR9 w/ Undershirt and Single-layer Jacket-closed	0.0169	2.1
FR9 w/ Undershirt and Double-layer Jacket-open	0.0187	2.6
FR9 w/ Undershirt and Double-layer Jacket-closed	0.0175	3.2

### *Thermal Characteristics of Clothing*

The principal utility of the WBGT-based heat stress evaluations represented by the TLV is to screen for potential heat stress in the workplace. They are, however, routinely exceeded. For a more in-depth analysis, a rational method is recommended. The ISO has one called Required Sweat Rate.<sup>20</sup> (The ISO will soon have a modification to this method called Predicted Heat Strain, but the rational nature remains the same.) The essence of the method is to determine the amount of evaporative cooling that is required for fully compensable heat stress or the maximum rate that can be sustained by the combination of environment and clothing for uncompensable heat stress. Knowing the thermal characteristics of the clothing is important for the model.

The basic thermal balance model is commonly expressed as some variation of Equation 1.<sup>20</sup>

$$S = (M + W) + R + C + E \quad (1)$$

The heat storage rate (S) reflects the net heat gain (positive values) to or loss (negative values) from the body. The net heat generated by metabolic demands from the work is equal to metabolic rate (M) (always a positive value) adjusted downward for the rate of external work performed (W) (always a negative value). R is the rate of radiant heat exchange between the skin and the environment. C represents the rate of convective heat transfer between the air and skin and lungs. E represents the rate of evaporative cooling due to the evaporation of water from the skin and lungs. The required evaporative cooling rate ( $E_{req}$ ) is the value that is sufficient to keep S near zero, but it is limited to the maximum value ( $E_{max}$ ) that is permitted by the environment and clothing.

Clothing can alter the rate of heat exchange between the body and the environment via radiation, convection, and evaporation. The total clothing insulation ( $I_t$ ) is a factor that accounts for a decrease in heat flow due to clothing and air insulation. The higher the value of  $I_t$ , the lower the rate of heat flow due to radiation and convection is. The total evaporative resistance ( $R_{e-t}$ ) is a factor that accounts for a decrease in water vapor flow due to clothing permeability. The higher the value of evaporative resistance, the less evaporative cooling occurs; hence, the higher the level of heat stress. Therefore, it is important to be aware of and account for the thermal properties of garments to prevent excessive exposure to heat stress. In practice, the dry heat exchange, which is modified by the clothing insulation, has a very small role at about 10%. The evaporative resistance or vapor permeability is clearly the most important thermal characteristic of clothing because evaporative cooling is the principal means of dissipating body heat.

At the critical point (the transition from the work-driven to the environmentally-driven zone, which is also the upper limit of the prescriptive zone), the required rate of evaporative cooling ( $E_{req}$ ) is equal to the maximum rate of evaporation ( $E_{max}$ ). At this point several relationships described by the following equations hold true.

$$E_{req} = - [(M + W) + (R + C) + (C + E)_{res} - S] \quad (2)$$

$$E_{max} = - (P_{sk} - P_a) / R_{e-t} \quad (3)$$

$$(R+C) = (T_{db} - T_{sk}) / I_t \quad (4)$$

By substituting Equations 3 and 4 into Equation 2, the following equation results.

$$(P_{sk} - P_a) / R_{e-t} = (M + W) + (C + E)_{res} - S + (T_{db} - T_{sk}) / I_t \quad (5)$$

Following the methods of Kenney, et al.,<sup>13</sup> metabolic rate ( $M$ ) in  $W/m^2$  is estimated from oxygen consumption in liters per minute as  $M = 351 V_{O_2} / A_D$ . The Dubois surface area ( $A_D$ ) is calculated for each subject as  $A_D = 0.202 m_b^{0.425} \cdot H^{0.725}$ , where  $m_b$  is the mass of the body (kg) and  $H$  is the height (m). The external work ( $W$ ) ( $W/m^2$ ) is calculated as  $W = -0.163 \cdot m_b \cdot V_w \cdot f_g / A_D$ , where  $m_b$  is body mass in kg,  $V_w$  is walking velocity in m/min,  $f_g$  is the fractional grade of the treadmill. Respiratory exchanges, latent respiration heat loss ( $E_{res}$ ) and dry respiration heat loss ( $C_{res}$ ), are calculated as  $C_{res} = 0.0012 \cdot M \cdot (T_{db} - 34)$  and  $E_{res} = 0.0173 \cdot M \cdot (P_a - 5.62)$ .

Kenney, et al.<sup>13</sup> 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 ( $0.97 W h/^\circ C kg$ ), body weight ( $m_b$ ), and the rate of change of body temperature ( $\Delta T_{re} / \Delta t$ ) as an average over the preceding 20 minutes before the inflection point was reached.<sup>17</sup> That is,  $S = 0.97 m_b \Delta T_{re} / A_D \Delta t$ .

Equation 5 provides a relationship that relates experimental conditions with clothing thermal characteristics at the inflection point when thermal balance is last achievable during escalating heat stress. Values for  $I_t$  and  $R_{e-t}$  are required to complete the equation. Values for  $I_t$  can be estimated. For instance, for woven-fabric clothing, the

method described by Olesen and Dukes-Dobos<sup>21</sup> and adjusted for air insulation as described by Parsons<sup>22</sup> can be used to estimate  $I_t$ . McCullough, et al.<sup>23</sup> reported values for  $I_t$  for many ensembles based on mannequin data. Because Havenith et. al.<sup>24</sup> found that the total insulation can drop by a factor of two for a person walking versus standing still and because further reductions may be expected from wet clothing,<sup>25</sup> the value of  $I_t$  estimated for clothing ensembles from bench tests or mannequin tests must be reduced.<sup>26</sup> The total evaporative resistance ( $R_{e-t}$ ) for each protocol and ensemble is then calculated from Equation 5 by using the estimated  $I_t$  values for that ensemble. The value of  $R_{e-t}$  is relatively insensitive to the estimated value of  $I_t$ , which means that we do not need a precise estimate.<sup>26</sup>

## Methods

### *General Methods*

#### Participants

The study protocol was approved by the USF IRB. A written informed 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. While smoking status was not an exclusionary factor, most were non-smokers.

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

Prior to beginning the experimental trials to determine critical WBGT, participants underwent a 5-day acclimatization period. Acclimatization to dry heat involved walking on a treadmill at a metabolic rate of approximately  $160 \text{ W m}^{-2}$  in a climatic chamber at  $50^\circ\text{C}$  and 20% relative humidity (rh) for two hours. Participants wore shorts (and sports bra for women), socks and shoes.

#### Clothing

Five different clothing ensembles were evaluated. The ensembles included work clothes (4 oz/yd<sup>2</sup> cotton shirt and 8 oz/yd<sup>2</sup> cotton pants), cotton coveralls (9 oz/yd<sup>2</sup>) and three limited-use protective clothing ensembles: particle-barrier ensembles (Tyvek® 1424 in the first year and 1427 in the second year), water-barrier, vapor-permeable ensembles (NexGen® LS 417), and vapor-barrier ensembles (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.

A cotton tee-shirt for men or sports bra with or without a tee-shirt for women and running shorts were worn under all clothing ensembles. Participants also wore socks and running shoes.

#### Equipment

The trials were conducted in a controlled climatic chamber. Temperature and humidity were controlled according to protocol and air speed was  $0.5 \text{ m s}^{-1}$ . Heart rate was monitored using a sports-type heart rate monitor (Polar Electro Inc, Lake Success,

NY). 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 on a motorized treadmill at a speed and grade set to elicit a target metabolic rate. Assessment of oxygen consumption was used to establish 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 minutes. The volume of expired air was measured using a dry gas meter. A Beckman E2 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 Exposure Protocols

In Year 1, the study design called for three environments: warm, humid at 70% relative humidity (R7); hot, dry at 20% relative humidity (R2); and a mid-range (50%) relative humidity (R5).

In the R7 protocol, the dry bulb temperature ( $T_{db}$ ) was set at 30°C and relative humidity (rh) at 70%. Once the participant reached thermal equilibrium (no change in  $T_{re}$  and heart rate for at least 15 minutes.),  $T_{db}$  was increased 0.7°C every 5 minutes. In the R2 protocol,  $T_{db}$  was set at 40°C with rh at 20%. When participants reached thermal equilibrium,  $T_{db}$  was increased 1°C every 5 minutes. For the R5 protocol,  $T_{db}$  was set at 34°C with 50% rh. Upon reaching thermal equilibrium,  $T_{db}$  was increased 0.8°C every 5 minutes.

In Year 2, the study design called for three target metabolic rates (150, 175 and 250 W m<sup>-2</sup> to represent light, moderate and heavy work. All trials were performed under the environmental conditions of  $T_{db}$  set at 34°C with 50% rh. Upon reaching thermal equilibrium,  $T_{db}$  was increased 0.8°C every 5 minutes.

The order of the ensemble-protocol (either environment or work demand) pairs was randomized. Any trial that had to be repeated was repeated at the end.

During trials, participants were allowed to drink water or a commercial fluid replacement beverage at will.

Core temperature, heart rate and ambient conditions (dry bulb, psychrometric wet bulb and globe temperatures;  $T_{db}$ ,  $T_{pwb}$  and  $T_g$ , respectively) were monitored continuously and recorded every 5 minutes. Trials were scheduled to last 120 minutes unless one of the following criteria was met: (1) a clear rise in  $T_{re}$  associated with a loss of thermal equilibrium (typically 0.1 °C increase per 5 min for 15 min), (2)  $T_{re}$  reached 39 °C, (3) a sustained heart rate greater than 90% of the age-predicted maximum heart rate, or (4) participant wished to stop.

### Inflection Point and Critical WBGT

The inflection point marks the transition from the work-driven zone to the environmentally-driven zone, which is the basis for WBGT occupational exposure limits. After the inflection point, core temperature continued to rise. Figure 1 illustrates core

temperature versus time for one trial. The chamber conditions five minutes before the noted increase in core temperature was taken as the critical condition. Usually one investigator noted the critical condition, and the decisions were randomly reviewed by a second investigator. The critical WBGT in °C was computed as  $0.7 (T_{pwb} + 1.0) + 0.3 T_g$  following the method described in O'Connor and Bernard.<sup>8</sup>

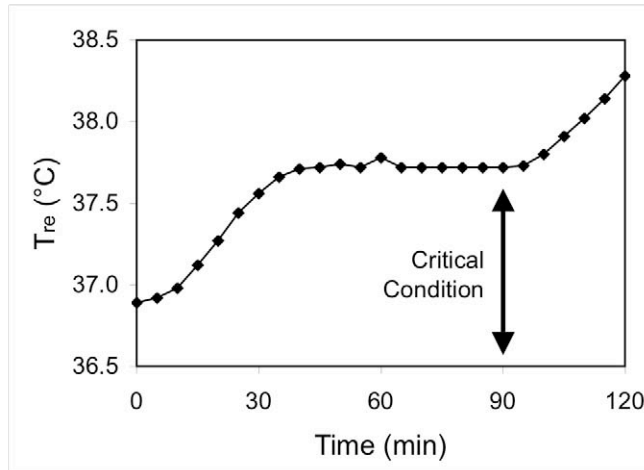


Figure 1. The time course of  $T_{re}$  for an example trial with an arrow to indicate the critical condition, the point 5 minutes prior to the steady increase in the environmentally driven zone.

#### Constant Exposure Protocol

The Year 3 study was based on a constant level of heat stress; that is, a fixed environment, metabolic rate and clothing ensemble. The heat stress levels were chosen to be uncompensable with higher levels expected to shorten the safe exposure time.

The order of the ensemble-heat stress pairs was randomized. Any trial that had to be repeated was repeated at the end.

During trials, participants were allowed to drink water or a commercial fluid replacement beverage at will.

Core temperature, heart rate and ambient conditions (dry bulb, psychrometric wet bulb and globe temperatures;  $T_{db}$ ,  $T_{pwb}$  and  $T_g$ , respectively) were monitored continuously and recorded every 5 minutes. Trials were scheduled to last 120 minutes unless one of the following criteria was met: (1)  $T_{re}$  reached 39 °C, (2) a sustained heart rate greater than 90% of the age-predicted maximum heart rate, or (3) participant wished to stop.

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, or (3) participant wished to stop.

#### *Methods for Year 1: Effects of Environment*

##### Participants

Fourteen adults (nine men and five women) participated in the experimental trials. The average and standard deviation of their physical characteristics by gender are provided in Table 2.

Table 2. Physical characteristics (mean  $\pm$  standard deviation) of the 14 participants in the Year 1 study.

	Number	Age (yr)	Height (cm)	Weight (kg)	Body Surface Area (m <sup>2</sup> )
Men	9	29.2 $\pm$ 6.8	183 $\pm$ 6	97.2 $\pm$ 18.5	2.18 $\pm$ 0.20
Women	5	31.8 $\pm$ 9.1	161 $\pm$ 7	63.5 $\pm$ 17.2	1.66 $\pm$ 0.23
All	14	30.1 $\pm$ 7.5	175 $\pm$ 12	85.2 $\pm$ 24.1	2.00 $\pm$ 0.33

#### Clothing

Five different clothing ensembles were evaluated: work clothes, cotton coveralls, Tyvek® 1424, NexGen® LS 417, and Tychem QC®.

#### Metabolic Rate

The target metabolic rate was 160 W m<sup>-2</sup> to approximate moderate work and was selected independent of aerobic capacity.

#### Environment

The effects of environment were evaluated by using the three environmental protocols: R2, R5 and R7.

#### *Methods for Year 2: Effects of Metabolic Rate*

##### Participants

Fifteen adults (eleven men and four women) participated in the experimental trials. The average and standard deviation of their physical characteristics by gender are provided in Table 3.

Table 3. Physical characteristics (mean  $\pm$  standard deviation) of the 15 participants in the Year 2 study.

	Number	Age (yr)	Height (cm)	Weight (kg)	Body Surface Area (m <sup>2</sup> )
Men	11	28.0 $\pm$ 9.5	176 $\pm$ 11	81.9 $\pm$ 11.7	1.98 $\pm$ 0.18
Women	4	23.0 $\pm$ 4.7	165 $\pm$ 6	64.2 $\pm$ 18.0	1.70 $\pm$ 0.22
All	15	26.7 $\pm$ 8.6	173 $\pm$ 11	77.2 $\pm$ 15.3	1.91 $\pm$ 0.22

#### Clothing

Five different clothing ensembles were evaluated: work clothes, cotton coveralls, Tyvek® 1427, NexGen® LS 417, and Tychem QC®. Note that the Tyvek ensemble was made of a different (newer) fabric in the Tyvek family.

#### Metabolic Rate

The target metabolic rates were 115, 175 and 250 W m<sup>-2</sup> to approximate light, moderate and heavy work and was selected independent of aerobic capacity.

## Environment

The R5 protocol was used for the evaluation of metabolic rate.

### *Methods for Year 3: Determination of Safe Exposure Limits*

#### Participants

Thirteen adults (9 men and 4 women) participated in the experimental trials in Year 3. The average and standard deviation of their physical characteristics by gender are provided in Table 4.

Table 4. Physical characteristics (mean  $\pm$  standard deviation) of the 13 participants in the Year 3 study.

	Number	Age (yr)	Height (cm)	Weight (kg)	Body Surface Area (m <sup>2</sup> )
Men	9	31.8 $\pm$ 10.4	182 $\pm$ 5	98.5 $\pm$ 13.7	2.19 $\pm$ 0.15
Women	4	28.0 $\pm$ 9.0	160 $\pm$ 7	66.1 $\pm$ 27.2	1.67 $\pm$ 0.33
All	13	30.6 $\pm$ 9.8	175 $\pm$ 12	88.5 $\pm$ 23.5	2.03 $\pm$ 0.32

#### Clothing

Three different clothing ensembles were evaluated, representing a range from work clothes to the most restrictive from an evaporative cooling point of view. The ensembles were work clothes, NexGen® LS 417, and Tychem QC®.

#### Metabolic Rate

The target metabolic rate a moderately high level of 190 W m<sup>-2</sup>.

#### Environment

The five time-limited environments were selected such that relative humidity was 50%. Table 5 lists the ambient WBGTs for each clothing ensemble and heat stress level. The ambient WBGTs were adjusted for an approximation of the clothing adjustment factor found in earlier trials.

Table 5. Target WBGTs at 50% relative humidity for the five heat stress levels across three clothing ensembles.

Level	Work Clothes	NexGen®	Tychem QC
1	36	33	29
2	37	34	30
3	38	36	32
4	40	38	34
5	44	41	38

**Results**

*Results for Year 1: Environment*

A 3-way ANOVA (analysis of variance) - (14 participants by 5 ensembles by 3 protocols) was performed on metabolic rate. There were significant differences among subjects ( $p < 0.001$ ) and among ensembles ( $p = 0.03$ ), where the metabolic rate was higher for Tychem QC ( $164 \text{ W m}^{-2}$ ) versus the other ensembles ( $150$  to  $155 \text{ W m}^{-2}$ ). There was no difference among protocols.

Table 6 provides the mean and standard deviation of the critical WBGTs for each pair of ensemble and protocol. Figure 2 illustrates the mean dry bulb temperature versus water vapor pressure at the critical conditions for the five clothing ensembles at each level of relative humidity. A 3-way ANOVA with interactions for critical WBGT (14 participants by 5 ensembles by 3 protocols with the ensemble by protocol interaction) (a fixed effects model) was performed. There were significant differences among participants ( $p < 0.001$ ), among ensembles ( $p < 0.001$ ), among humidity protocols ( $p = 0.002$ ) and with the interaction of ensemble by protocol ( $p < 0.001$ ).

Table 6. Mean ( $\pm$  standard deviation) of Critical WBGTs ( $^{\circ}\text{C}$ ) and number of observations for each combination of clothing ensemble and environmental protocol and for the pooled Critical WBGTs by ensemble; and the slope of the three Critical WBGTs for each ensemble as plotted on a psychrometric chart.

Ensemble	Environmental Protocol			Pooled	Slope [kPa/ $^{\circ}\text{C}$ ]
	R2	R5	R7		
Work Clothes	$35.0 \pm 1.56$ n=13	$34.8 \pm 1.19$ n=14	$33.9 \pm 1.79$ n=15	$34.5 \pm 1.58$ n=42	-0.17
Cotton Coveralls	$34.4 \pm 2.25$ n=14	$35.4 \pm 1.61$ n=15	$33.2 \pm 1.71$ n=15	$34.3 \pm 2.05$ n=44	-0.16
Tyvek® 1424	$33.3 \pm 2.75$ n=14	$33.8 \pm 1.15$ n=14	$33.3 \pm 1.30$ n=15	$33.4 \pm 1.84$ n=43	-0.20
NexGen®	$31.8 \pm 1.78$ n=15	$32.8 \pm 1.87$ n=18	$32.6 \pm 1.43$ n=13	$32.4 \pm 1.75$ n=46	-0.23
Tychem QC®	$23.8 \pm 2.23$ n=16	$26.6 \pm 1.57$ n=15	$28.9 \pm 1.93$ n=14	$26.3 \pm 2.83$ n=45	-0.84

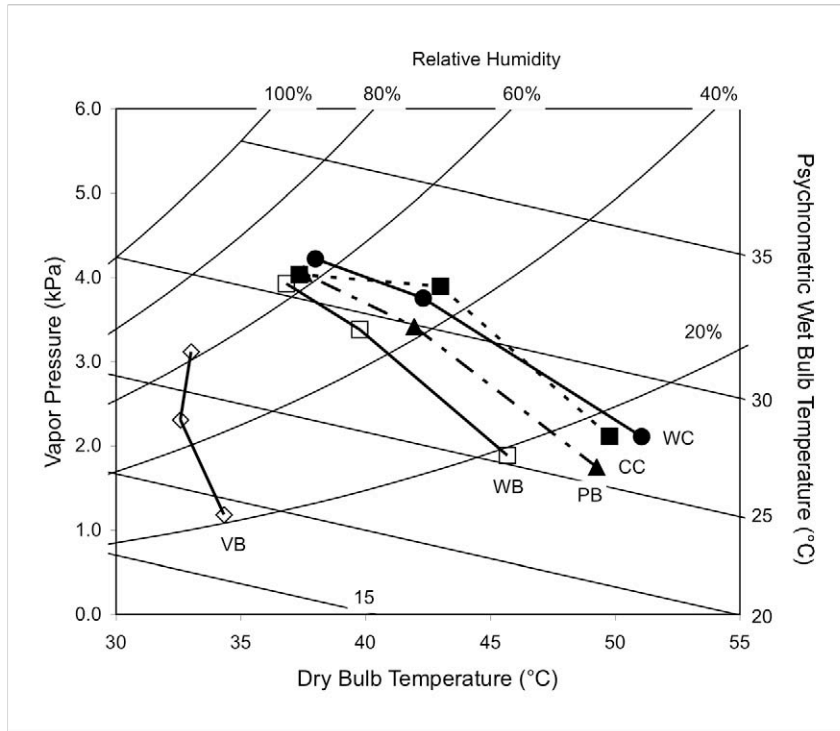


Figure 2. The location on a psychrometric chart of the average critical conditions for each ensemble and relative humidity protocol pair, where WC is work clothes, CC is cotton coveralls, PB is Tyvek® 1424, WB is NexGen® and VB is Tychem QC®.

A second 3-way ANOVA as described above without Tychem QC was performed, and the interaction term was non-significant at  $\alpha = 0.05$ . Based on this outcome, the data were re-categorized such that each Tychem QC and humidity protocol pair was treated as an ensemble. A 2-way ANOVA (14 participants by 7 ensembles) was used in the final analysis of critical WBGTs. There were significant differences among participants ( $p < 0.001$ ) and ensembles including the Tychem QC-protocol pairs ( $p < 0.001$ ). An adjusted multiple comparison test on all possible pairs was completed. The results are provided in Table 7. There were no significant differences between work clothes and cotton coveralls; cotton coveralls and Tyvek 1424; and Tyvek 1424 and NexGen. All other comparison pairs were significantly different at  $\alpha = 0.05$ .

Table 7. Least Squares Estimate of Critical WBGT for each ensemble with the Tychem QC® (vapor barrier) ensemble divided into environmental protocols, the results of the pair-wise comparisons and the proposed clothing adjustment factor.

Ensembles†	Pair-wise Comparisons*	Critical WBGT (°C) [LS Mean]	WBGT Difference from Work Clothes (°C)	Proposed Clothing Adjustment Factor (°C-WBGT)
Work Clothes		34.4	---	---
Cotton Coveralls		34.2	0.2	0
Tyvek® 1424		33.2	0.8	1
NexGen®		32.4	2.0	2
Tychem QC®		26.3	8.1 -- Pooled	10
- Tychem QC® in R7		29.0	5.4	
- Tychem QC® in R5		26.6	7.8	
- Tychem QC® in R2		23.0	11.4	

† All ensembles but work clothes in a coverall configuration without hood and gloves.

\* Lines indicate no difference between ensembles at the  $\alpha = 0.05$  level.

A second focus of this research was to determine the effects of environment and metabolic rate on evaporative resistance ( $R_{e,t}$ ) among the five selected ensembles. A mixed model analysis of variance with participant ( $n=14$ ), ensemble ( $n=5$ ) and protocol ( $n=3$ ) as the main effects. The ensemble by protocol interaction was also evaluated. A Tukey's Honestly Significant Difference (HSD) was used to test all pair-wise comparisons among  $R_{e,t}$ . Mean  $R_{e,t}$  are presented in Table 8.

Table 8. Mean and standard deviation of  $R_{e,T}$  ( $\text{kPa m}^2 \text{W}^{-1}$ ) for Year 1 trials

	All Data†	R2	R5	R7	
Work Clothes	0.013 $\pm 0.0040$		0.017 $\pm 0.0035$	0.012 $\pm 0.0029$	0.011 $\pm 0.0029$
Cloth Coveralls	0.014 $\pm 0.0047$		0.018 $\pm 0.0046$	0.012 $\pm 0.0035$	0.012 $\pm 0.0035$
Tyvek 1424	0.015 $\pm 0.0052$		0.020 $\pm 0.0042$	0.014 $\pm 0.0043$	0.013 $\pm 0.0047$
NexGen	0.017 $\pm 0.0053$		0.021 $\pm 0.0039$	0.016 $\pm 0.0051$	0.014 $\pm 0.0046$
Tychem	0.027 $\pm 0.0089$		0.034 $\pm 0.0100$	0.026 $\pm 0.0051$	0.021 $\pm 0.0065$

† The differences were based on a two stage analysis of the data, where the second stage excluded Tychem.

There were significant differences among participants, ensembles and environments ( $p < 0.001$ ). Tychem QC® had a significantly greater  $R_{e,t}$  than all other ensembles, and NexGen® had a significantly greater  $R_{e,t}$  than work clothes or cotton coveralls. The variance for Tychem QC® was much greater than the other ensembles and could have interfered with the ability to differentiate differences among ensembles. When the data was analyzed without Tychem QC®, the  $R_{e,t}$  for NexGen® was greater than all other ensembles and  $R_{e,t}$  for work clothes was significantly less than Tyvek 1424®.

There was also a significant difference in  $R_{e,t}$  among environments. Figure 3 graphically presents the mean  $R_{e,t}$  data by environment. The ensemble-environment interaction was significant ( $p=0.019$ ) and is also seen in Figure 3.

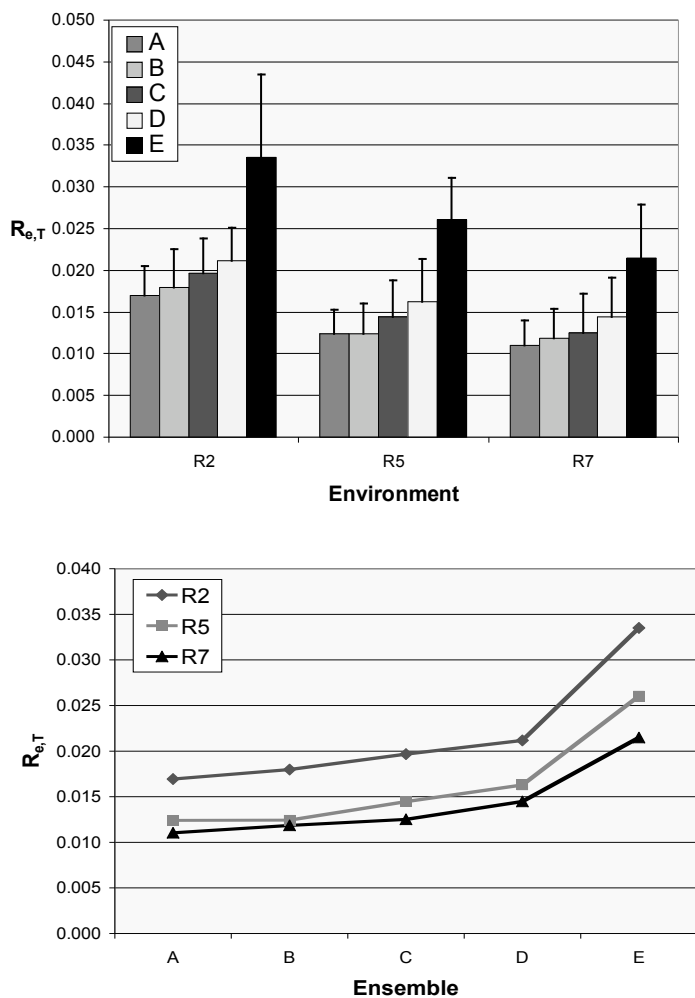


Figure 3. Mean values of total evaporative resistance ( $R_{e,t}$ ,  $\text{kPa m}^2 \text{W}^{-1}$ ) by clothing ensemble and level of humidity. A -- Work Clothes; B -- Cloth Coveralls; C -- Tyvek; D -- NexGen; and E -- Tychem. R2 -- 20% rh; R5 -- 50% rh; and R7 -- 70% rh.

With the evident interaction between total evaporative resistance and environment as reflected in relative humidity, the relationship between  $R_{e,T}$  and the water vapor pressure gradient between the skin and the environment was examined. Figure 5 shows the relationship for work clothes. Significant linear relationships were found for each ensemble.

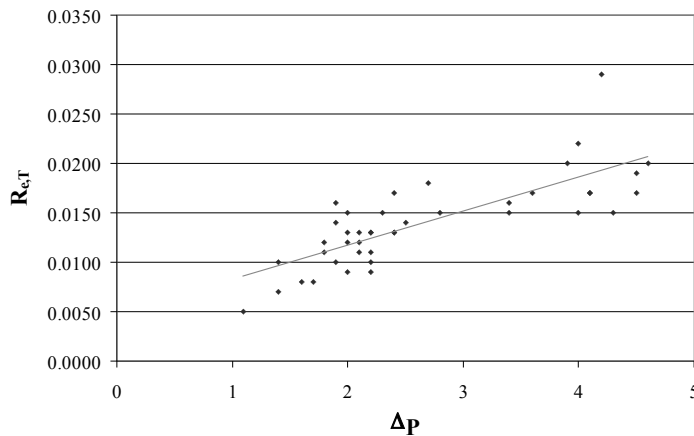


Figure 5. Relationship between computed value for total evaporative resistance and the gradient of water vapor pressure from the skin to the ambient environment.

#### *Results for Year 2: Metabolic Rate*

A 3-way ANOVA (analysis of variance) - (15 participants by 5 ensembles by 3 protocols) was performed on metabolic rate. There were significant differences among subjects ( $p < 0.001$ ). Per the study design, there were significant differences among protocols ( $p < 0.001$ ). There was no difference among ensembles.

Table 9 provides the mean Critical WBGTs for each combination of metabolic rate and ensemble. A 3-way ANOVA with interactions for Critical WBGT (15 participants by 5 ensembles by 3 metabolic rates with the ensemble by metabolic rate interaction) was performed. There were significant differences among participants ( $p < 0.001$ ), among metabolic rates ( $p < 0.001$ ), and among ensembles ( $p < 0.001$ ). There was no significant interaction ( $p = 0.52$ ). Table 9 also provides the least squares mean of Critical WBGT for each ensemble and for each metabolic rate. As expected, critical WBGT was significantly different for all metabolic rates with the greatest WBGT seen for the lowest metabolic rate. The critical WBGT was lowest for Tychem QC®, significantly greater for NexGen®, and greatest for cotton work clothes, cotton coveralls and Tyvek® 1424.

Table 9. Mean ( $\pm$  standard deviation) of Critical WBGTs ( $^{\circ}$ C) and number of observations for each combination of clothing ensemble and metabolic rate protocol and the least squares mean for Critical WBGTs and change from work clothes by ensemble and from Moderate metabolic rate by metabolic rate.

Ensemble	LS Mean	Change	Metabolic Rate		
			Light 114 W m <sup>2</sup>	Moderate 177 W m <sup>2</sup>	Heavy 250 W m <sup>2</sup>
Work Clothes	33.8	0	36.6 $\pm$ 1.13 n=14	33.6 $\pm$ 1.42 n=15	31.0 $\pm$ 1.57 n=15
Cotton Coveralls	33.5	0.2	35.8 $\pm$ 1.14 n=14	33.7 $\pm$ 1.14 n=14	31.0 $\pm$ 1.75 n=14
Tyvek® 1427	33.3	0.5	35.7 $\pm$ 1.59 n=16	33.6 $\pm$ 1.34 n=15	30.6 $\pm$ 1.72 n=15
NexGen®	31.7	2.1	34.4 $\pm$ 0.92 n=15	31.5 $\pm$ 1.17 n=15	29.1 $\pm$ 1.44 n=15
Tychem QC®	27.5	6.2	30.8 $\pm$ 1.69 n=16	27.3 $\pm$ 1.84 n=15	24.6 $\pm$ 2.09 n=17
LS Mean			34.6	31.9	29.3
Change			2.7	0	-2.6

Also of interest was the effects of metabolic rate on evaporative resistance ( $R_{e,t}$ ) among the five selected ensembles. A mixed model analysis of variance with participant (n=15), ensemble (n=5) and protocol (n=3) as the main effects. The ensemble by protocol interaction was also evaluated. A Tukey’s Honestly Significant Difference (HSD) was used to test all pair-wise comparisons among  $R_{e,t}$ . Mean  $R_{e,t}$  are presented in Table 10.

Table 10. Mean and standard deviation of  $R_{e,T}$  (kPa m<sup>2</sup> W<sup>-1</sup>) for Year 2 trials

Ensemble	All Data	Light	Moderate	Heavy
Work Clothes	0.011 $\pm$ 0.002	0.011 $\pm$ 0.002	0.013 $\pm$ 0.003	0.011 $\pm$ 0.001
Cloth Coveralls	0.012 $\pm$ 0.003	0.014 $\pm$ 0.003	0.012 $\pm$ 0.002	0.011 $\pm$ 0.003
Tyvek 1427	0.013 $\pm$ 0.003	0.015 $\pm$ 0.004	0.012 $\pm$ 0.002	0.011 $\pm$ 0.001
NexGen	0.015 $\pm$ 0.004	0.018 $\pm$ 0.005	0.015 $\pm$ 0.002	0.012 $\pm$ 0.002
Tychem	0.024 $\pm$ 0.006	0.028 $\pm$ 0.005	0.024 $\pm$ 0.004	0.019 $\pm$ 0.003

Significant differences were found among participants (p<0.001), among ensembles(p<0.001) and among metabolic rates (p<0.002). NexGen® and Tychem QC®

were significantly greater than the other ensembles and significantly different from each other. The  $R_{e,t}$  was greatest for the low metabolic rate and lowest for the high level of metabolic rate. In addition, the interaction between ensemble and metabolic rate was significant. These data are presented graphically in Figure 5.

When the relationship between total evaporative resistance and water vapor pressure gradient was examined, there was no significant correlation.

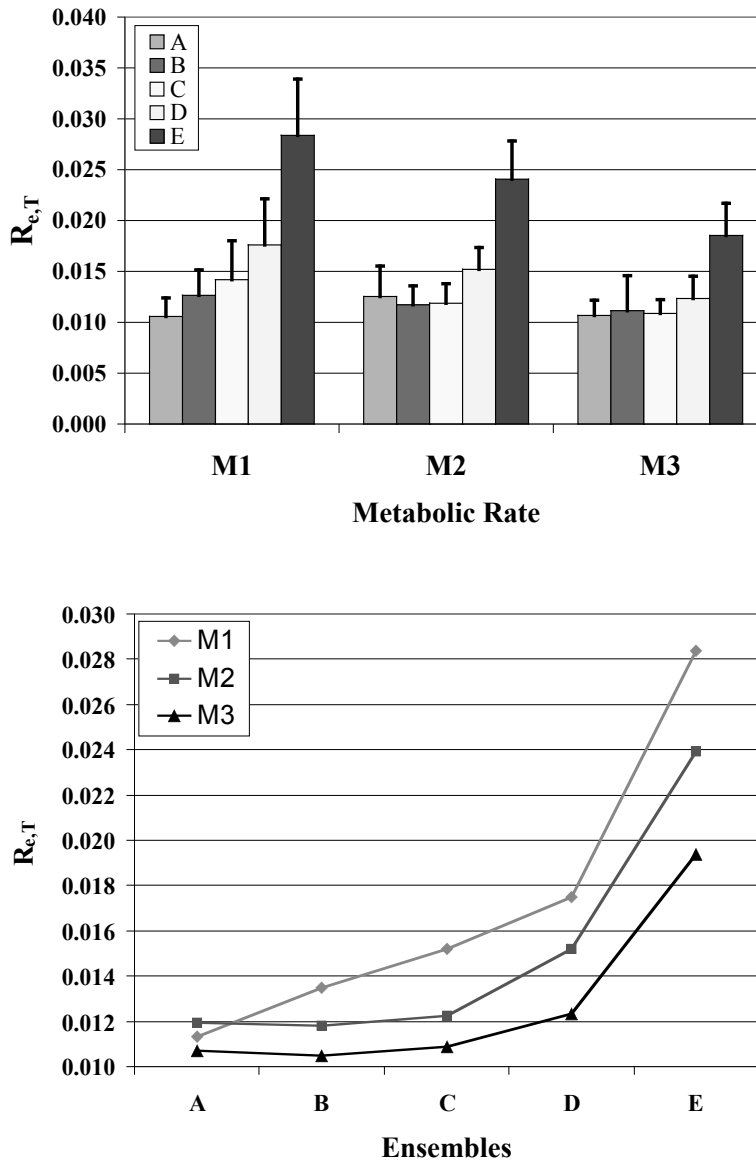


Figure 5. Mean values of total evaporative resistance ( $R_{e,T}$ ,  $\text{kPa m}^2 \text{W}^{-1}$ ) by clothing ensemble and level of metabolic rate. A -- Work Clothes; B -- Cloth Coveralls; C -- Tyvek; D-- NexGen; and E -- Tychem. M1 -- Light; M2 -- Moderate; and M3 -- Heavy.

*Results for Year 3: Time-Limited Exposures*

On the surface, the design for Year 3 looks like a complete factorial with participants, ensemble and heat stress levels as the treatments. Looking at metabolic rate in a 3-way ANOVA, there are significant differences among participants but there are no differences for ensemble or heat stress level. The average metabolic rate was 188 W m<sup>-2</sup>.

Because the environmental conditions were selected with the ensemble in mind, the heat stress level is nested within ensemble for the purpose of analysis. Using the safe exposure time as the dependent variable, an ANOVA with heat stress level nested in ensemble was performed. Table 11 summarizes the safe exposure times for the combinations of ensemble and heat stress level. An initial analysis of the data pointed to anomalous data for NexGen at Heat Stress Level 2, in which they were systematically higher than expected from the other data for NexGen and from the data for work clothes and Tychem QC. For this reason, all the data in that cell were not included in the data analysis described in this paragraph. The ANOVA based on the nested design indicated significant effects for participants, ensembles and heat stress level. While a significant difference was detected by the ANOVA, Tukey's HSD did not distinguish among the ensembles. For the heat stress levels, Tukey's HSD pointed to some overlap between pairs of ensembles and heat stress levels, but generally each heat stress level was different from the others and the ensembles within each heat stress level were not different.

Table 11. Mean ( $\pm$ standard deviation) for safe exposure time for the three clothing ensembles by five heat stress levels.

Heat Stress Level	Work Clothes	NexGen	Tychem
1	77.7 $\pm$ 17.0	77.4 $\pm$ 30.2	77.4 $\pm$ 14.3
2	60.5 $\pm$ 20.4	96.5 † $\pm$ 27.6	61.7 $\pm$ 20.1
3	55.1 $\pm$ 15.7	49.3 $\pm$ 14.1	55.5 $\pm$ 12.6
4	38.1 $\pm$ 7.5	39.9 $\pm$ 7.9	46.5 $\pm$ 5.5
5	25.7 $\pm$ 6.5	27.9 $\pm$ 9.2	33.0 $\pm$ 6.5
LS Mean	50.3	50.2	55.5

† Data not considered in this analysis

A survival analysis was then used to analyze the complete data set. The dependent variable was safe exposure time, and the independent variables were normalized metabolic rate, WBGT and ensemble. Trials that were stopped at 120 minutes were censored as non-events, all other data were included. As expected, metabolic rate was not significant because it was controlled within the trials and it was

dropped from the analysis. Based on the results, 95% survival curves of WBGT versus time were computed for the three ensembles. These are shown in Figure 6.

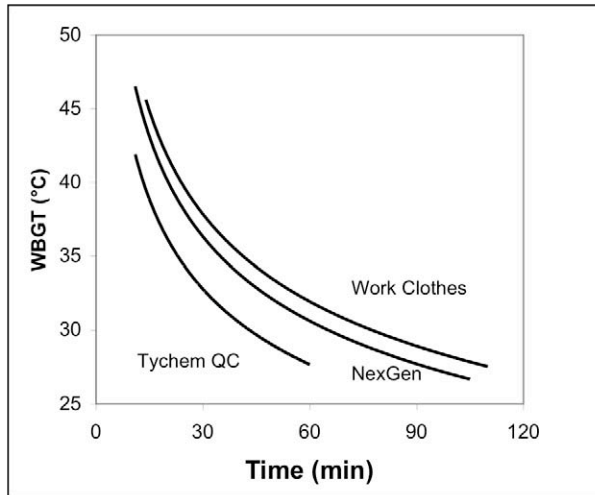


Figure 6. Safe exposure time based on 95% survival curves for WBGT and ensemble ( $M=380$  W).

## Discussion

### *Year 1: Environment, Critical WBGT and Clothing Adjustments*

The critical WBGT was explored for five clothing ensembles at three levels of relative humidity. One of the important experimental controls was the metabolic rate normalized to body surface area. The normalized metabolic rate for one of the ensembles (Tychem QC) was  $10 \text{ W m}^{-2}$  or 7% higher than the others. Teitlebaum and Goldman<sup>27</sup> found a 10% increase in metabolic rate when five layers of additional clothing were worn. Because there was no difference in the number of layers in the present study, there is no reason to believe that the Tychem QC clothing added to the metabolic rate. Bernard and Joseph<sup>28</sup> argued that a difference of 27 W (nominally  $15 \text{ W m}^{-2}$  for a body surface area of  $1.8 \text{ m}^2$ ) was equivalent to a  $0.5 \text{ }^\circ\text{C}$  difference in WBGT based on the TLV curve at a moderate metabolic rate. The relationship can be expressed as  $-0.034 \text{ }^\circ\text{C-WBGT m}^2 \text{ W}^{-1}$ . This would suggest that the observed mean Tychem QC WBGT could be  $0.4 \text{ }^\circ\text{C}$  lower because of the higher metabolic rate. For work clothes and flame-retardant clothing, Cortés-Vizcaino and Bernard<sup>29</sup> reported an average difference of  $-0.7 \text{ }^\circ\text{C-WBGT}$  among six pairs of data (three participants and two ensembles) in critical WBGT when the differences in metabolic rate were greater (275 versus 350 W or a nominal  $40 \text{ W m}^{-2}$  difference). While not statistically significant, the difference supports a bias that is about  $-0.018 \text{ }^\circ\text{C-WBGT m}^2 \text{ W}^{-1}$ . O'Conner and Bernard<sup>8</sup> reported 34 pairs of metabolic rates which were not statistically different with an average difference of  $-0.007 \text{ }^\circ\text{C-WBGT m}^2 \text{ W}^{-1}$ . Because (1) the acceptable accuracy for WBGT is about  $0.5 \text{ }^\circ\text{C}$ , and (2) the greatest difference in metabolic rates are not biased by more than  $0.5 \text{ }^\circ\text{C}$ , the differences in metabolic rates among the ensembles were considered acceptable for

comparison purposes in the present study without discounting for the increase in metabolic rate for the vapor barrier clothing.

The next step was to characterize the critical environments as a critical WBGT for a moderate rate of work. When a 3-way ANOVA with interactions of ensemble and relative humidity was used to analyze the critical WBGT data, it became clear that the interaction between the vapor-barrier ensemble (Tychem QC) and relative humidity was statistically significant. Figure 2 plots the critical WBGT at each of the three relative humidity levels for the five ensembles in present study. It is clear that the slope of the line representing the vapor-barrier ensemble is steeper than the others. By removing the Tychem QC ensemble from the analysis, the significant interaction between ensembles and relative humidity disappeared. The first major implication for this finding was that WBGT adequately accounted for the interaction of temperature and relative humidity as they affect the critical conditions for four of the ensembles.

When looking at the relationship between water vapor pressure and dry bulb temperature on a psychrometric chart, a constant WBGT has a slope of about  $-0.18$  kPa/°C. The slope of a least squares fit of the three mean values for each ensemble in Figure 2 are given in Table 6. Excluding the vapor barrier ensemble the slopes range from  $-0.16$  to  $-0.23$ . For their ensembles, Kenney et al.<sup>30</sup> found similar relationships for woven clothing. Recalculated values from their Table II were  $-0.20$ ,  $-0.16$ , and  $-0.21$  kPa/°C for work clothes, cotton anti-contamination coveralls and double cotton anti-contamination coveralls, respectively. The slopes of the non-vapor-barrier clothing in both studies are similar and close to that associated with WBGT. This supports the finding that critical WBGT does not change with humidity. In contrast, the slope for the vapor barrier ensemble in the present study was  $-0.84$  compared to  $-0.24$  kPa/°C for a limited-use vapor-barrier coverall over anti-contamination coveralls of Kenney et al.<sup>(14)</sup> While the previously reported slope for vapor-barrier clothing would suggest little effect of humidity on critical WBGT, that cannot be concluded from the present study. The steeper slope suggested a different balancing of dry bulb temperature and vapor pressure with more weight given to the air temperature. We will return to this below.

Because there was no interaction between relative humidity level and ensemble for work clothes, coveralls, Tyvek 1424 (non-woven particle barrier) and NexGen (non-woven liquid-barrier, vapor permeable), the critical WBGT was an appropriate measure of the clothing contribution to heat stress at a moderate rate of work. Using the work clothes as a baseline, WBGT adjustments for other clothing ensembles can be assigned as the observed difference across humidity levels. Table 7 contains suggested adjustment factors for coveralls, Tyvek 1424 and NexGen clothing ensembles.

For coveralls, no real difference was found when compared to work clothes. This was in contrast to other guidance. A 2°C adjustment for anti-contamination coveralls in the nuclear power industry (with hood and gloves) was suggested by Bernard, Kenney and Balint<sup>11</sup> based on professional judgment. This has been repeated in other sources such as earlier versions of the ACGIH TLV for heat stress. A re-examination of Kenney's data<sup>16</sup> suggested that the average difference between work clothes and the anti-contamination coveralls that he studied was closer to 3.6 to 4.0 °C. This value has also found its way into other clothing guidance including the current ACGIH TLV for heat

stress and strain.<sup>31</sup> In the Kenney study,<sup>16</sup> the reference work clothes and the anti-contamination coveralls were studied in different labs with different participants. In the present study, the coveralls were worn as a work uniform without hood and gloves and no taping of the cuffs. Further, the same laboratory and participants were used to directly compare the work clothes to coveralls, which makes a stronger statistical statement.

The interaction between the vapor-barrier ensemble (Tychem QC) and relative humidity level posed a problem. A perfect vapor-barrier (infinite evaporative resistance) would not be influenced by humidity at all;<sup>31</sup> that is, it would have an infinite slope on a psychrometric chart. The steeper slope for vapor-barrier clothing in the present study (see Table 6) would suggest a high evaporative resistance. To account for the higher evaporative resistance in a WBGT framework, Antuñano and Nunneley<sup>32</sup> have suggested a re-weighting of the natural wet bulb and globe temperatures for ensembles with limited evaporative cooling capacity such that the weighting of  $T_{db}$  and  $T_{wb}$  would be 0.5 and 0.5 following the Heat-Humidity Index. The only weighting that can provide a constant WBGT for the three humidity conditions would be 0.15 for natural wet bulb and 0.85 for globe temperature. That results in a heavy emphasis on dry heat exchange and much less emphasis on humidity and evaporative cooling. Taking this approach means that the method of calculating WBGT must be adjusted for clothing ensembles in addition to shifting the threshold on a critical environment. This approach is cumbersome and a departure from the simplicity of WBGT-based assessments.

Because there were three significantly different critical WBGTs for the three relative humidity levels in the vapor-barrier ensemble, either an adjustment for each relative humidity level must be proposed or one value that favors the high end of the range would be appropriate. Table 7 suggests an adjustment of about 10 °C, which is consistent with other recommendations for vapor-barrier clothing<sup>16-19</sup> and does recognize the fact that the configuration was a coverall in the present study and not configured with a hood as in the other studies.

In summary, a practical accounting for four clothing ensembles during heat stress exposures at moderate metabolic rate is provided in the form of clothing adjustment factors. The clothing adjustment factor can be added to the measured WBGT and then compared to an occupational exposure limit. The only significant compromise was the need to take a more protective adjustment for vapor-barrier clothing. It is necessary to demonstrate in further investigations that the clothing adjustment factors are applicable at lower and higher metabolic rates.

### *Year 2: Metabolic Rate, Critical WBGT and Clothing Adjustments*

The clothing adjustment factors that evolve out of the Year 1 and Year 2 data are summarized in Table 12. Overall there is very good agreement between the two years and associated study designs. The improvement (lower difference) for Tyvek was expected with the change of fabric. The Year 1 value for Tychem was for the similar relative humidity between the two years for a more fair comparison. While the second year was lower by 1.6 °C-WBGT, it still points to a substantial effect due to the vapor-barrier nature of the fabric. More important was the finding that there was no interaction for Critical WBGT between metabolic rate and the clothing ensemble. This means that

the clothing adjustment factors remain sufficiently constant independent of the metabolic rate and the clothing.

Table 12. Clothing adjustments based on the data for Year 1 (different environments) and Year 2 (different metabolic rates).

Ensemble	Year 1	Year 2
Work Clothes	0	0
Cloth Coveralls	0.2	0.2
Tyvek 1424/1427	0.8	0.5
NexGen	2.0	2.1
Tychem	7.8†	6.2

† For the 50% rh (R5) trials only

The goal in heat stress assessment is to balance the internal heat gain from metabolic rate with the ability to dissipate the heat to the environment. Knowing the effect for clothing is a constant (see previous paragraph), then the trade-off between WBGT and metabolic rate becomes interesting. A multiple linear regression of Critical WBGT against normalized metabolic rate suggested a slope of  $-0.033 \text{ }^{\circ}\text{C-WBGT m}^2 \text{ W}^{-1}$ . This relationship is very similar to that reported by others over a more narrow range of metabolic rates. For instance as described in the Year 1 discussion above, Cortés-Vizcaino and Bernard<sup>29</sup> reported about  $-0.018 \text{ }^{\circ}\text{C-WBGT m}^2 \text{ W}^{-1}$ , and O’Conner and Bernard<sup>8</sup> reported an average difference of  $-0.007 \text{ }^{\circ}\text{C-WBGT m}^2 \text{ W}^{-1}$ .

#### *Years 1 and 2: Total Evaporative Resistance*

Experimental trials were conducted in Years 1 and 2 to determine the evaporative resistance for five selected clothing ensembles. The protocols included a fixed metabolic demand under three different relative humidity levels for Year 1, and for three metabolic demands with a fixed relative humidity level for Year 2.

#### *Internal Validity*

Year 1 and 2 both had one protocol that had the same design -- a moderate work rate ( $160 \text{ W m}^{-2}$ ) and a moderate humidity (50% rh). The Tyvek ensemble fabric was changed between Year 1 and 2, but the other ensembles remained the same. Comparing the moderate work rate and moderate environment (Moderate - R5) data from both years provided internal validity to the methodology. The mean  $R_{e,T}$  values for ensembles for Year 1 and 2 were virtually the same except for the Tyvek ensemble, which was less in Year 2 than in Year 1 as expected. A one-way ANOVA found a difference between years only for the Tyvek ( $p = 0.035$ ).

#### *Clothing Insulation*

In order to determine the evaporative resistance, an estimate of clothing insulation is needed. The clothing insulation values for this study were developed from manikin experiments conducted at the Institute for Environmental Research, Kansas State University by Dr. Elizabeth McCullough<sup>23</sup>. Following ASTM F 1291, she was able to

determine the total clothing insulation ( $I_{T,stat}$ ) for the six ensembles used in the experimental trials. As reported by Havenith et al.<sup>33</sup> heated manikin results for standing/no wind appear to be on average  $0.023 \text{ } ^\circ\text{C m}^2 \text{ W}^{-1}$  higher than human participants. After adjusting for wind and movement, the  $I_{T,dyn}$  values were set. These values are provided in Table 13.

Table 13. Values of static and dynamic clothing insulation for the five ensembles.

Ensemble	$I_{T,stat}$	$I_{T,dyn}$
Work Clothes	0.180	0.147
Cloth Coveralls	0.196	0.160
Tyvek	0.191	0.156
NexGen	0.189	0.154
Tychem	0.185	0.151

Having a good estimate of  $I_{T,dyn}$  is important because it is used to compute  $R_{e,T}$ . However, Barker et al.<sup>27</sup> demonstrated that relatively large changes in  $I_{T,dyn}$  result in minor changes in  $R_{e,T}$ . Therefore the manikin data adjusted for wind and movement is sufficient for determining the  $I_{T,dyn}$  of the ensembles used.

#### Total Evaporative Resistance

At the inflection point, critical conditions exist where  $S = 0$  and  $E_{max} = E_{req}$ . From these conditions the basic heat balance equation can be manipulated by substituting terms for  $E_{max}$  and  $E_{req}$  and solving for  $R_{e,T}$  following Equation 5 (page 8). Average values for total evaporative resistance are provided in Table 14.

Table 14. Total evaporative resistance ( $R_{e,T}$ ) ( $\text{kPa m}^2 \text{ W}^{-1}$ ) values from the current study and three other published sources.

Ensemble	Current	Barker	Kenney	Bernard
Work Clothes	0.0133	0.0131	0.0092	
Cloth Coveralls	0.0140	0.0159	0.0096	0.0155
Tyvek 1427	0.0154	0.0163	0.0112	
NexGen	0.0174	0.0176	0.0123	
Tychem	0.0273	0.0136	0.0344	

Barker et al.<sup>27</sup> reported three  $R_{e,T}$  values that were within 6%, one at 14% and one at 50% (vapor barrier suit). The values of Kenney et al.<sup>34</sup> ranged from 26 – 32% difference, and Bernard and Mattheen<sup>35</sup> reported values 11% higher. The  $I_T$  values of Barker<sup>27</sup> were close to the ensembles used in this study with the exception of not adjusting these values by 45% to account for wettedness. However, even with the 45% difference in  $I_T$ , there is minor differences in  $R_{e,T}$ . Barker et al.<sup>27</sup> had previously reported this relationship, and this studies supports it. Based on the Barker et al.<sup>27</sup> and Bernard and Mattheen<sup>35</sup> studies, the  $R_{e,T}$  values calculated in this study appears in line with other reported values.

## Year 1

The methodology used was able to distinguish differences among the selected ensembles as illustrated in Table 8. Since Tychem QC is a vapor barrier suit, it is expected to be different from ensembles that do not prevent vapor transmission such as cotton and Tyvek coveralls. Similarly, NexGen (liquid barrier suit) was also expected to be different from particle barrier and cotton clothing with respect to evaporative resistance.

In Figure 3, there is a clear difference among environments. The differences among the mean  $R_{e,T}$  values remains the same within work clothes, cloth coveralls, Tyvek 1424 and NexGen, but increases for Tychem QC. The increase difference accounts for the interaction between the environment and ensemble and was verified when the data was analyzed without Tychem QC.

## Year 2

Similar to Year 1, the methodology used was able to distinguish among the selected ensembles as illustrated in Table 10 showing very significant differences of NexGen and Tychem QC as compared to work clothes, cloth coveralls and Tyvek. Figure 5 indicates that  $R_{e,T}$  decreases as the metabolic rate increases. The interaction between ensemble and metabolic rate is clearly seen by observing the differences among metabolic rates within each ensemble. There was little difference in the mean  $R_{e,T}$  values among the metabolic rates within work clothes indicating good evaporative cooling (high permeability). However, progressing through the ensembles, the differences between protocols increases indicating the metabolic rate (activity) plays an increasing role in lowering the mean  $R_{e,T}$ . Statistically, work clothes and cloth coveralls were not significantly different whereas the others (Tyvek, NexGen and Tyvek QC coveralls) were significantly different from each other.

Havenith et al.<sup>25</sup> and Parsons et al.<sup>36</sup> explain the relative decrease in  $R_{e,T}$  due to the increased air movement through the clothing. They used the term pumping action to explain that as an individual moves, air is pumped into and out of their clothing. As the air moves through the clothing, the effective insulation and total evaporative resistance decrease due to increased convective and evaporative cooling.

## Total Evaporative Resistance and Water Vapor Pressure Gradient

The relationship between  $\Delta P$  with respect to  $E_{max}$  (Equation 3) assumes that remains constant as  $\Delta P$  and  $E_{max}$  change. Figure 5 clearly shows that  $R_{e,T}$  was not constant as the environment changes. Using the data from Years 1 and 2, a regression analysis of  $\Delta P$  against  $R_{e,T}$  was performed. Table 15 presents the correlation coefficients from the regression analysis. Significant relationships were found for each ensemble in Year 1. Significant relationships were not seen in the Year 2 data when the effect of metabolic rate confounded (balanced) the effects of gradient. The higher metabolic rate required a greater gradient to support the added heat loss requirement, but it also decreased the total evaporative resistance by increasing the pumping effect.

Table 15. Regression correlation coefficients for  $\Delta P$  by  $R_{e,T}$

Ensemble	Year 1 $R^2$	Year 2 $R^2$
Work Clothes	0.617	0.115
Cloth Coveralls	0.453	0.018
Tyvek 1427	0.477	0.001
NexGen	0.388	0.001
Tychem	0.534	0.005

### Summary for Total Evaporative Resistance

Experimental trials were conducted to determine the total evaporative resistance for five clothing ensembles. The protocols included a fixed metabolic demand under three different environments (levels of relative humidity) for Year 1, and a fixed relative humidity level with three metabolic demands with for Year 2. The fundamental step in these studies was identifying the point just before the transition from compensable heat stress to uncompensable heat stress ( $E_{req} = E_{max}$ ).

From Year 1, the vapor-barrier fabric of Tychem QC was different from all others and the water-barrier of NexGen was different from woven clothing (work clothes and cloth coveralls). These relative differences were also seen in Year 2 for different metabolic rates.

Further, a relationship with the level of humidity in environment was found in Year 1. This effect was confounded by metabolic rate via the pumping effect in Year 2.

### *Year 3: Heat Stress Level, Clothing and Safe Exposure Time*

The metabolic rate across all of the combinations of ensemble and heat stress level were the same and therefore there should be no confounding of the results. It should be noted that the metabolic rate was at the high end of moderate work ( $190 \text{ W m}^{-2}$  or about  $380 \text{ W}$ ).

A casual inspection of Table 11 suggests that each of the heat stress levels has about the same average safe exposure time. There was some bias in the selection of WBGTs for each heat stress level because NexGen and Tychem QC were targeted for lower WBGTs by 2.5 and 7 °C, respectively. These values were approximations of the clothing adjustment factors based on preliminary analyses of Years 1 and 2 data. For main effects, the Tychem had a higher LS mean than work clothes or NexGen, and this appeared to be due to longer times in the two higher heat stress levels. This would argue for a higher clothing adjustment for Tychem QC and the 8 °C found for Year 1 data at 50% rh appears reflect the clothing effect. The Tukey's HSD analysis found no statistically significant differences among ensembles within heat stress levels. Overall there is fair evidence to suggest that the clothing adjustment factors apply to uncompensable heat stress as well as compensable heat stress near the occupational exposure limit.

The survival analysis was used to place a lower time limit (95% survival) as a function of WBGT for each clothing ensemble. The results were illustrated in Figure 6.

Figure 7 shows the time limit versus the actual data for work clothes. The curve may lack some protection below 20 minutes and appears to be overly protective above 45 minutes. The safe time limit line reaches the occupational exposure limit based on the ACGIH TLV at 380 W at 90 minutes. The limit curve has the following equation

$$t_{\text{safe exp}} [\text{min}] = 8.23 \times 10^7 / \text{WBGT} [^\circ\text{C}]^{4.08} \quad (6)$$

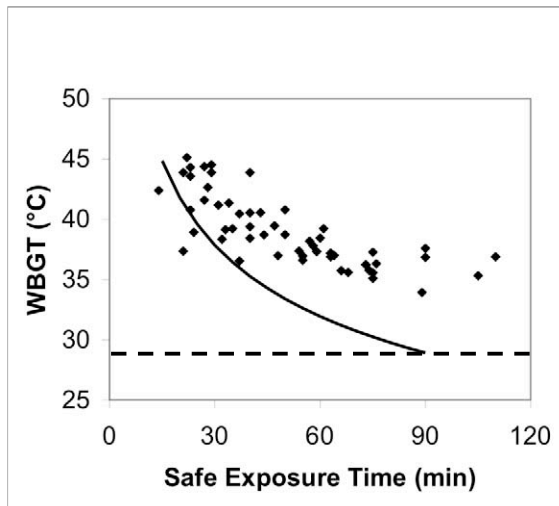


Figure 7. Individual data and 95% line for safe exposure time (min) versus WBGT (M=380 W) for work clothes. Dashed line represents the occupational exposure limit for continuous exposure.

Over most of the range of the curves in Figure 6, the NexGen is about 1.5°C lower than work clothes and Tychem QC is about 4.5 °C lower. Using the recommended adjustment of 2 °C for NexGen is further supported for the time-limited applications of the curve. It appears that the adjustment for Tychem of 10 °C (or even the 7.8 associated with 50% rh) might be overly protective. Using the line based on work clothes and adjusted downward by 7.8 °C-WBGT, the line in Figure 8 is created. Comparing it against the data collected in Year 3 for Tychem, it appears that the line is adequately protective to about 60 minutes and over protective above that time. Therefore, using a clothing adjustment factor appears adequate, with similar overprotection at longer times (lower WBGTs). In practice, the 10 °C-WBGT adjustment for vapor-barrier clothing like Tychem QC is necessary to cover the inability of WBGT to predict heat stress over the range of humidities for vapor-barrier clothing found in Year 1.

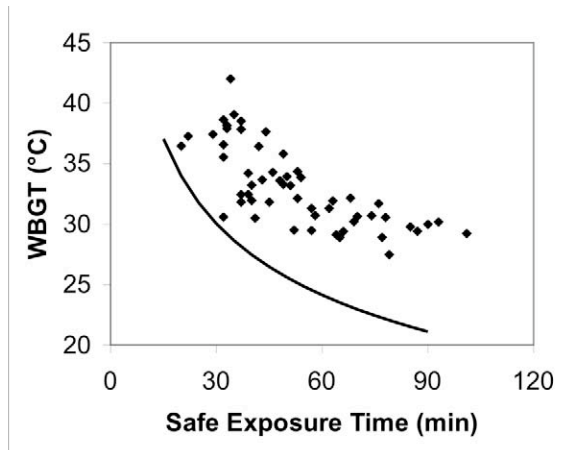


Figure 8. Individual data for Tychem QC and proposed time limit line (M=380 W) based on work clothes and shifted down by the clothing adjustment factor for Tychem QC (7.8 °C at 50% rh).

## Conclusions

### *Clothing Adjustment Factors*

Traditional heat stress assessment is based on a wet bulb globe temperature (WBGT) threshold that is adjusted for the metabolic rate of the work. The threshold was based on cotton work clothes (long sleeved shirt and pants). The overall purpose of this NIOSH sponsored research effort was to make traditional WBGT methods of exposure assessment relevant to common (woven and non-woven) protective clothing ensembles. The method chosen to account for clothing ensembles that differ from work clothes was the Clothing Adjustment Factor. The essence of the Clothing Adjustment Factor is to add a value to the ambient WBGT that represents the added heat stress due to the clothing.

In the first phase of the research project (called Year 1), the clothing adjustments for four clothing ensembles were determined. The clothing was cloth (cotton) coveralls, limited-use particle barrier coveralls (Tyvek 1424), limited-use water-barrier, vapor-permeable coveralls (NexGen), and vapor-barrier coveralls (Tyvek QC). The recommended Clothing Adjustment Factors are provided in Table 16.

Table 16. Recommended Clothing Adjustment Factors (CAFs) for four clothing ensembles in a coveralls configuration.

<b>Ensemble</b>	<b>CAF [°C]</b>	<b>CAF [°F]</b>
Work Clothes (Reference)	0	0
Cloth Coveralls	0	0
Limited-Use Particle Barrier Coveralls (specifically Tyvek 1427) Note: From previous research, an SMS fabric is likely to have a -1 °C CAF	0.5	1
Limited-Use Water-Barrier, Vapor-Permeable Coveralls (specifically NexGen) Note: A wide variation in CAFs are expected for the films and laminates that provide the barrier properties.	2	4
Limited-Use Vapor-Barrier Coveralls (specifically Tychem QC) Note: The actual vapor-barrier fabric is not critical in establishing the CAF.	10	18

The first phase of the research demonstrated that the WBGT index and the associated Clothing Adjustment Factor works well over a range of humidities for those ensembles that allowed some sweat loss through the fabric. This was not true for the vapor-barrier ensemble. For this reason, a near worst case factor (10 °C) was selected rather than the average over the environments (8 °C). The second phase of the study (Year 2) examined the possibility that different work demands, which have different metabolic rates as well as body movements, might have an effect on the Clothing Adjustment Factor. The results suggest that the adjustments hold true over a wide range of metabolic rates from 230 to 500 W. The third phase (Year 3) provided some evidence that the clothing adjustments also apply to uncompensable heat stress.

### *Safe Exposure Time*

Often a heat stress exposure is greater than the occupational exposure limit for continuous exposures. An interesting question is what might the safe exposure time be. The third phase of the research effort began to address this question. For a moderate to high metabolic rate (380 W), a time limit curve to maintain body core temperature and heart rates at acceptable levels 95% of the time was postulated. This can be used to control heat stress exposures for intervals from about 20 to 90 minutes. The determination of time is based on a three step process. The first step is to assign a WBGT adjustment for the clothing. This is the Clothing Adjustment Factor from Table 16 or elsewhere.

The safe exposure curve is based on a metabolic rate (M) of 380 W. The second step is to adjust the WBGT to account for the metabolic rate. From Year 2, the adjustment is  $-0.033 \text{ } ^\circ\text{C-WBGT m}^2 \text{ W}^{-1}$  or about  $-0.017 \text{ } ^\circ\text{C-WBGT W}^{-1}$ . Combining the first and second steps, the following equation can be used generate an equivalent WBGT starting with the ambient WBGT.

$$\text{WBGT}_{\text{equiv}} [\text{C}] = \text{WBGT}_{\text{amb}} [^{\circ}\text{C}] + \text{CAF} [^{\circ}\text{C}] + 0.017 (\text{M} [\text{W}] - 380) \quad (7)$$

Then the third step is to compute the safe exposure time from Equation 8, which is a restatement of Equation 6 using the equivalent WBGT.

$$t_{\text{safe exp}} [\text{min}] = 8.23 \times 10^7 / \text{WBGT}_{\text{equiv}}^{4.08} [^{\circ}\text{C}] \quad (8)$$

This approach may be weakest at the shortest times (higher WBGTs) and clearly protective at times between 30 and 90 minutes. At greater than 90 minutes, the occupational exposure limit should be used. Further examination of time limits is likely to refine the judgments and a topic for further efforts.

#### *Total Evaporative Resistance*

The determination of total evaporative resistance made use of manikin data for insulation and adjusted for air motion and body motion. The process was able to distinguish among the different ensembles. This will aid understanding how different fabrics and configurations rank against existing or prototypes. The study did find that total evaporative resistance depends on metabolic rate, which has been known from other studies, and on the water vapor pressure gradient between the skin and the air. This dependency was not observed before. The implications for using the information in rational heat stress models is open for discussion.

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### **In Review**

Ashley, C. D., S. W. Schwartz, V. Caravello, T. E. Bernard. Gender differences in critical environment and heat strain for five clothing ensembles. *Aviation, Space and Environmental Medicine*

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