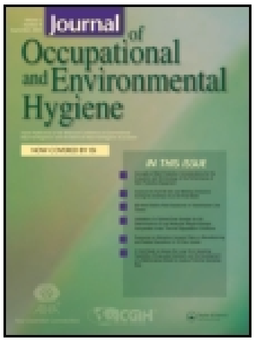

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WBGT Clothing Adjustments for Four Clothing Ensembles Under Three Relative Humidity Levels

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Threshold limit values for heat stress and strain are based on an upper limit wet bulb globe temperature (WBGT) for ordinary work clothes, with clothing adjustment factors (CAF) for other clothing ensembles. The purpose of this study was to determine the CAF for four clothing ensembles (Cotton Coveralls, Tyvek® 1424 Coveralls, NexGen® Coveralls, and Tychem QC® Coveralls) against a baseline of cotton work clothes and to determine what effect relative humidity may have. A climatic chamber was used to slowly increase the level of heat stress by increasing air temperature at three levels of relative humidity (20%, 50%, and 70%). Study participants wore one of the five ensembles while walking on a treadmill at a moderate metabolic rate of 155 W m^{-2} (about 300 W). Physiological data and environmental data were collected. When the participant's core temperature reached a steady state, the dry bulb temperature was increased at constant relative humidity. The point at which the core temperature began to increase was defined as the inflection point. The environmental temperature recorded 5 min before the inflection point was used to calculate the critical WBGT for each ensemble. A three-way analysis of variance with ensemble by humidity protocol interactions and a multiple comparison test were used to make comparisons among the mean values. Only the vapor-barrier ensemble (Tychem QC) demonstrated an interaction with humidity level. The following CAFs are proposed: Cotton Coveralls (0°C–WBGT), Tyvek 1424 Coveralls (+1), NexGen Coveralls (+2), and Tychem QC Coveralls (+10).

Keywords heat stress, protective clothing, TLV

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Heat stress evaluation requires knowledge of the role clothing plays as well as the environment and work demands. Clothing insulation reduces the effects of dry heat exchange (i.e., convection and radiation), while evaporative resistance modifies the maximum rate of evaporative cooling. These features of clothing are accounted for in rational heat stress evaluation methods such as the one adopted by the International Organization for Standardization (ISO)(1) and proposed to the ISO.(2)

As an alternative to rational methods of heat stress evaluation, the wet bulb globe temperature (WGBT) is widely used in the assessment of the environmental conditions for occupational heat stress. Because WBGT-based assessments are based on observed (empirical) relationships and not rational (biophysical) relationships, it is more difficult to account for clothing effects based on insulation and evaporative resistance. For this reason, offsets or adjustments for clothing in WBGT units have been sought. In essence, the adjustment factor represents an equivalent change of environmental WBGT. Clothing adjustment factors were first proposed by Ramsey;(3) furthered by Bernard, Kenney, and Balint,(4) and Kenney(5); and first adopted by the American Conference of Governmental Hygienists (ACGIH®) in 1990, with some changes in the following years.(6) O'Connor and Bernard(7) summarized the findings of a variety of studies performed in their laboratory.

Kenney(5) compared work clothes with 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 anticontamination protection in nuclear power plants; the vapor barrier was a polyethylene film on Tyvek® fabric. While Kenney's 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.(7) Using Kenney's mean work clothes values as a reference,(8) 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(5) (based on the difference between two standard deviations from the mean) would suggest a value around 9°C to 11°C for the vapor-barrier ensemble. This lower difference was similar to reports by Paull and Rosenthal(9) and Reneau and Bishop.(10)

The current study was undertaken with a representative range of clothing, including newer fabrics not available during past studies. A moderate rate of work was selected, which is similar to other studies. The critical WBGTs were computed for all clothing ensembles at three levels of relative humidity using all participants to minimize the effects of individuals and study procedures.

METHODS

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 I. The study protocol was approved by the University of South Florida Institutional Review Board. 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 nonsmokers.

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 W m^{-2} in a climatic chamber at 50°C and 20% relative humidity (RH) for 2 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^2 cotton shirt and 8 oz/yd^2 cotton pants), cotton coveralls (9 oz/yd^2) and three limited-use protective clothing ensembles: particle-barrier ensembles (Tyvek 1424), 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 T-shirt for men or sports bra with or without a T-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 $m/^{sec-1}$. Heart rate was monitored using a sports-type heart rate monitor (Polar Electro Inc, Lake Success, N.Y.). Core temperature was measured with a flexible thermistor inserted 10 cm beyond the anal sphincter muscle. The thermistor was calibrated prior to each trial using a hot water bath.

The work demand consisted of walking on a motorized treadmill at a speed and grade set to elicit a target metabolic rate of about 160 W m^{-2} to approximate moderate work and was selected independent of aerobic capacity. 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 min. 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 min into a trial and expressed as the rate normalized to body surface area.

Protocols

The study design called for three environments: warm, humid at 70% relative humidity (R7); hot, dry at 20% relative humidity (R2); and a midrange (50%) relative humidity (R5). Each ensemble was worn in each environment for a total of 15 trials per participant. Most participants completed one trial per day, but some completed two trials per day with at least 3 hours of recovery between trials.

In the R7 protocol, the dry bulb temperature (T_{db}) was set at 30°C and relative humidity at 70%. Once the participant reached thermal equilibrium (no change in T_{re} and heart rate for at least 15 min), T_{db} was increased 0.7°C every 5 min. 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 min. For the R5 protocol, T_{db} was set at 34°C with 50% RH. On reaching thermal equilibrium, T_{db} was increased 0.8°C every 5 min.

The order of the ensemble-environment conditions 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.

TABLE I. Physical Characteristics (mean ± standard deviation)

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

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 min. Trials were scheduled to last 120 min 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 Determination of 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 5 min 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.[7]

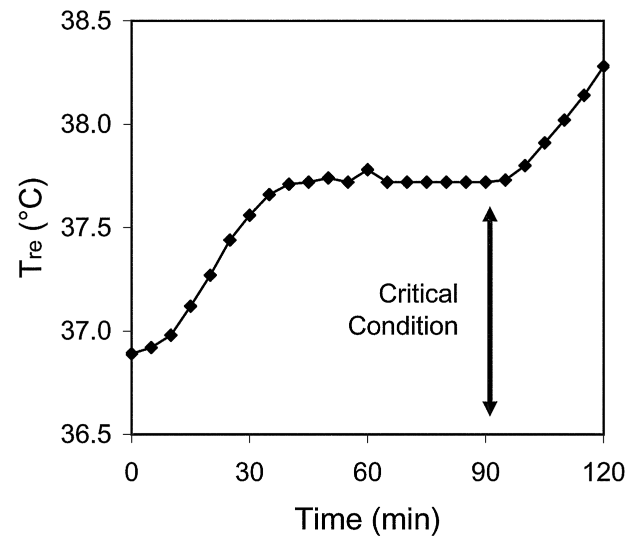

FIGURE 1. The time course of T_{re} for an example trial with an arrow to indicate the critical condition—the point 5 min prior to the steady increase in the environmentally driven zone.

RESULTS

A three-way analysis of variance (ANOVA), (14 participants by five ensembles by three 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 W m^{-2}) versus the other ensembles (150 to 155 W m^{-2}). There was no difference among protocols.

Table II 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 three-way ANOVA with interactions for critical WBGT (14 participants by five ensembles by three 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 ($p < 0.001$).

A second three-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 recategorized such that each Tychem QC and humidity protocol pair was treated as an ensemble. A two-way ANOVA, 14 participants by seven 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

TABLE II. Mean (± standard deviation) of Critical WBGTs

	Environmental Protocol				
Ensemble	R2	R5	R7	Pooled	Slope (kPa/°C)
Work clothes	35.0 ± 1.56 n = 13	34.8 ± 1.19 n = 14	33.9 ± 1.79 n = 15	34.5 ± 1.58 n = 42	−0.17
Cotton coveralls	34.4 ± 2.25 n = 14	35.4 ± 1.61 n = 15	33.2 ± 1.71 n = 15	34.3 ± 2.05 n = 44	−0.16
Tyvek 1424	33.3 ± 2.75 n = 14	33.8 ± 1.15 n = 14	33.3 ± 1.30 n = 15	33.4 ± 1.84 n = 43	−0.20
NexGen	31.8 ± 1.78 n = 15	32.8 ± 1.87 n = 18	32.6 ± 1.43 n = 13	32.4 ± 1.75 n = 46	−0.23
Tychem QC	23.8 ± 2.23 n = 16	26.6 ± 1.57 n = 15	28.9 ± 1.93 n = 14	26.3 ± 2.83 n = 45	−0.84

Note: n = number of observations.

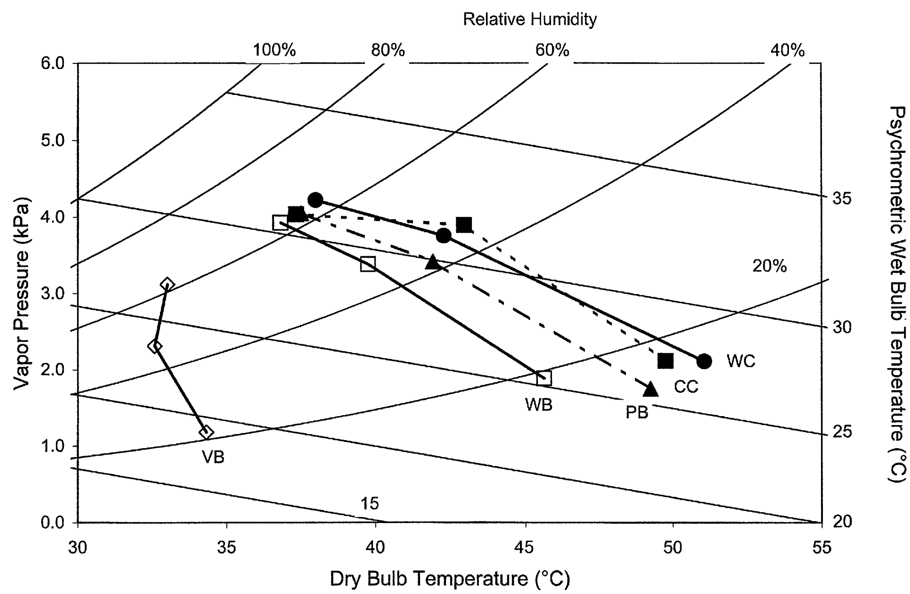

FIGURE 2. The location on a psychrometric chart of the average critical conditions for each ensemble and relative humidity protocol pair, where WC is work clothes, CC is cotton coveralls, PB is Tyvek 1424, WB is NexGen, and VB is Tychem QC.

comparison test on all possible pairs was completed. The results are provided in Table III. 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 $\alpha = 0.05$.

DISCUSSION

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 W m^{-2} or 7% higher than the others. Teitlebaum and Goldman[11] 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[12] argued that a difference of 27 W (nominally 15 W m^{-2} for a body surface area of 1.8 m^2) was equivalent to a 0.5°C difference in WBGT based on the TLV curve at a moderate metabolic rate. The relationship can be expressed as 0.34 °C–WBGT/10 W m^{-2}. This would suggest that the observed mean Tychem QC WBGT could be 0.4°C lower because of the higher metabolic rate.

For work clothes and flame-retardant clothing, Cortés-Vizcaino and Bernard[13] reported an average difference of 0.7°C–WBGT among six pairs of data (three participants and

TABLE III. Least Squares Estimate of Critical WBGT for Each Ensemble

Ensembles^A	Pair-Wise Comparisons^B	Critical WBGT (°C)	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	

^{A}All ensembles but work clothes in a coverall configuration without hood and gloves.
^{B}Lines indicate no difference between ensembles at the $\alpha = 0.05$ level.

two ensembles) in critical WBGT when the differences in metabolic rate were greater (275 versus 350 W or a nominal 40 W m^{-2} difference). While not statistically significant, the difference supports a bias that is about 0.18°C–WBGT per 10 W m^{-2}.

O'Conner and Bernard[7] reported 34 pairs of metabolic rates that were not statistically different with an average difference of 0.07°C–WBGT per 10 W m^{-2}. Because (1) the acceptable accuracy for WBGT is about 0.5°C, and (2) the greatest difference in metabolic rates are not biased by more than 0.5°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 three-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 psychometric 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 II. Excluding the vapor barrier ensemble the slopes range from −0.16 to −0.23. For their ensembles, Kenney et al.[14] 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 anticontamination coveralls and double cotton anticontamination coveralls, respectively. The slopes of the nonvapor-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 with −0.24 kPa/°C for a limited-use vapor-barrier coverall over anticontamination coveralls of Kenney et al.[14] 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 (nonwoven particle barrier) and NexGen (nonwoven 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 III contains suggested adjustment factors for coveralls and Tyvek 1424 and NexGen clothing ensembles.

For coveralls, no real difference was found when compared with work clothes. This was in contrast to other guidance. A 2°C adjustment for anticontamination coveralls in the nuclear power industry (with hood and gloves) was suggested by Bernard, Kenney, and Balint[4] based on professional judgment. This has been repeated in other sources such as earlier versions of the ACGIH® TLV® for heat stress. A reexamination of Kenney's data[5] suggested that the average difference between work clothes and the anticontamination coveralls that he studied was closer to 3.6°C 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.[6] In the Kenney study,[5] the reference work clothes and the anticontamination 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 with 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;[15] 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 II) would suggest a high evaporative resistance.

To account for the higher evaporative resistance in a WBGT framework, Antuñano and Nunneley[16] have suggested a reweighting 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 III suggests an adjustment of about 10°C, which is consistent with other recommendations for vapor-barrier clothing[5,8–10] 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.

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