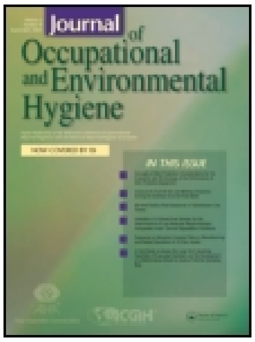

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Journal of Occupational and Environmental Hygiene

ISSN: 1545-9624 (Print) 1545-9632 (Online) Journal homepage: http://www.tandfonline.com/loi/uoeh20

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To cite this article: Candi D. Ashley & Thomas E. Bernard (2007) Effects of Hoods and Flame-Retardant Fabrics on WBGT Clothing Adjustment Factors, Journal of Occupational and Environmental Hygiene, 5:1, 59-62, DOI: 10.1080/15459620701764358

To link to this article: https://doi.org/10.1080/15459620701764358

Journal of Occupational and Environmental Hygiene, 5: 59–62
ISSN: 1545-9624 print / 1545-9632 online

DOI: 10.1080/15459620701764358

Effects of Hoods and Flame-Retardant Fabrics on WBGT Clothing Adjustment Factors

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Personal protective clothing (PPC) may include hoods and flame-retardant (FR) fabrics that may affect heat transfer and, thus, the critical wet bulb globe temperature ($WBGT_{crit}$) to maintain thermal equilibrium. The purpose of this study was to compare the differences in $WBGT_{crit}$ for hooded vs. nonhooded versions of particle barrier and vapor barrier coveralls as well as for coveralls made of two flame-retardant fabrics (INDURA cotton and Nomex). Acclimated men (n = 11) and women (n = 4) walked on a treadmill in a climatic chamber at 180 W/m^2 wearing four different ensembles: limited-use, particle barrier coveralls with and without a hood (Tyvek 1427), and limited-use vapor barrier coveralls with and without a hood (Tychem QC, polyethylene-coated Tyvek). Twelve of the participants wore one of two flame-retardant coveralls. All participants wore standard cotton clothing. Progressive exposure testing at 50% relative humidity (rh) was designed so that each subject established a physiological steady-state followed by a clear loss of thermal equilibrium. $WBGT_{crit}$ was the WBGT 5 min prior to a loss of thermal equilibrium. Hooded ensembles had a lower $WBGT_{crit}$ than the nonhooded ensembles. The difference suggested a clothing adjustment of 1°C for hoods. There were no significant differences among the FR ensembles and cotton work cloths, and the proposed clothing adjustment for FR coveralls clothing is 0°C.

Keywords heat stress, protective clothing, WBGT

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INTRODUCTION

The American Conference of Governmental Industrial Hygienists (ACGIH®) threshold limit value (TLV) for heat stress[1] was developed with the assumption that cotton work clothes would be worn. Because protective clothing affects the level of heat stress, investigators have developed clothing adjustment factors to reflect the change in heat stress imposed by different clothing ensembles as it differs from cotton work clothes. The empirical rationale for clothing adjustment factors was first implied by Paull and Rosenthal.[2] They compared the microclimate WBGT while wearing protective clothing and compared it with the ambient WBGT to suggest the effect of impermeable, encapsulating clothing. Reneau et al.[3] interpolated a clothing adjustment factor for encapsulating clothing (e.g., MOPP wear and Level B) by comparing WBGTs for compensable and uncompensable heat stress. The clothing adjustment factors should fall between these two environmental conditions.

The idea of a critical environment was first proposed by Kenney[4] for accounting for protective clothing, and his approach was extended by O'Connor and Bernard[5] in determining a critical WBGT and was further refined by Bernard et al.[6,7] Most of the fabrics studied at the University of South Florida (USF) were either cotton or a nonwoven polymer and were worn in a one-piece coverall configuration without a head covering.

Hoods are commonly worn to protect against chemical splashes, particulate matter, and rain. Because the head contributes 7% to total cutaneous evaporation at 35°C,[8] a hood represents an obstacle to evaporative cooling. Further, it would reduce evaporative cooling by reducing the convective transfer of water vapor. With regard to two common FR fabrics (treated cotton and polymer fibers), there was anecdotal information to suggest that there is a perceptual difference among them. Bernard and Cortes-Vizcaino[9] found no difference in critical WBGT between cotton work clothes and a flame-retardant ensemble of a Zirpo wool shirt and FR8 denim pants.

The primary purpose of this study was to examine the additional heat stress contributed by hooded ensembles against the nonhooded version. A secondary purpose was to compare coveralls made of two common flame-retardant fabrics against standard work clothes to see whether there was a difference from work clothes.

METHODS

Clothing

Two hooded ensembles were compared with their non-hooded counterparts. The ensembles included limited-use, particle barrier coveralls (Tyvek 1427; DuPont, Wilmington, Del.) and limited-use vapor barrier coveralls (Tychem QC, polyethylene-coated Tyvek; DuPont). The limited-use coveralls had a zipper closure in the front and elastic around the wrists and ankles. The two flame-retardant coveralls designed for hot environments were made of INDURA treated cotton fabric (7 oz/yd^2 or 237 g/m^2; Westex, Chicago, Ill.) and Nomex (4.5 oz/yd^2 or 152 g/m^2; Dupont). These ensembles were compared against work clothes (4 oz/yd^2 or 135 g/m^2 cotton long sleeve shirt, 8 oz/yd^2 or 270 g/m^2 cotton pants). The base ensemble was athletic shoes and socks, shorts, and cotton t-shirt or sports bra for women, which was worn underneath test ensembles.

Participants

The main study examining the effects of hooded ensembles used a convenience sample that included 15 healthy adults (4 women and 11 men). Means and standard deviations of their physical characteristics are provided in Table I. Of these, 12 participants wore one of two coveralls of a flame-retardant fabric (n = 6 for INDURA and n = 6 for Nomex); all 15 wore standard work clothes.

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 nonsmokers. Women self-reported results of a home pregnancy test. Any woman who was pregnant was excluded from the study. 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 hr before the appointment and not to participate in vigorous exercise before the trial.

Prior to beginning the experimental trials, participants underwent a 5-day acclimatization period wearing the base ensemble. Acclimatization to dry heat involved daily walking on a treadmill at a speed and grade to elicit a metabolic rate of approximately 180 W/m^2 in a climatic chamber set at 50°C and 20% relative humidity (rh). Acclimatization lasted for 2 hr or until one of the termination criteria was met. Termination criteria included rectal temperature (T_{re}) greater than 39°C, sustained heart rate (HR) greater than 90% of age-predicted maximum HR, participant wished to stop, or 120 min had elapsed.

TABLE I. Summary of Participant Characteristics

	Age	Height (cm)	Weight (kg)	BSA (m^2)
Women (n = 4)	23 ± 5	165 ± 6	64.2 ± 18.0	1.70 ± 0.22
Men (n = 11)	28 ± 10	176 ± 11	81.7 ± 12.0	1.98 ± 0.47
Both (n = 15)	27 ± 9	173 ± 11	77.0 ± 15.4	1.91 ± 0.22

Equipment

Experiments were conducted in a controlled climatic chamber. Participants walked on a Stair Master Club Track treadmill (Nautilus, Inc., Vancouver, Wash.) at a speed and grade set to elicit a metabolic rate of 180 W/m^2. Heart rate was monitored using a Polar Electro Heart Rate Monitor (Polar Electro Inc., Lake Success, N.Y.). Rectal temperature was measured using a flexible YSI 401AC thermistor (Yellow Springs Instruments, Yellow Springs, Ohio) inserted 10 cm past the anal sphincter muscle. The rectal thermistor was calibrated prior to each trial using a hot water bath. Skin temperature (T_{sk}) was monitored at four sites (chest, upper arm, thigh, calf) using YSI 409A thermistors (Yellow Springs Instruments), and average skin temperature was computed.

To assess oxygen consumption, expired gases were collected by asking participants to breathe through a two-way valve into a collection bag for approximately 2.5 min. The volume of expired air was measured using a dry gas meter, and the oxygen content was measured using a Beckman Model E2 oxygen analyzer (Beckman Inc., Pasadena, Calif.). The metabolic rate recorded for each trial was the average of three samples of oxygen consumption taken at approximately 30, 60, and 90 min into a trial and expressed as the metabolic rate normalized to body surface area.

Protocols

Experimental sessions were conducted in each of the ensembles in a moderate environment, initially held constant at 34°C and 50% rh. When the participants reached thermal equilibrium (no change in HR or T_{re} for 15 min), T_{db} was increased 1°C every 5 min. The order in which the ensembles were worn during trials was randomized, with any necessary repeated trials completed at the end. During the trials, participants were allowed to drink water or a commercial fluid replacement beverage as desired

Ambient conditions (dry bulb, psychrometric wet bulb and globe temperatures; T_{db}, T_{pwb} and T_g, respectively), HR and T_{re} were monitored continuously and recorded every 5 min and T_{sk} was recorded every 10 min. Trials lasted approximately 120 min unless termination criteria were met. Termination criteria included successful completion of the trial (determination of critical WBGT), a T_{re} above 39°C, a HR of 90% age-predicted max, a clear rise in T_{re} associated with a loss of thermal equilibrium, or by request of the participant. The critical WBGT in °C was computed as $0.7\,(T_{pwb} + 1.0) + 0.3\,T_g$ and determined following the rationale described in O'Connor and Bernard[5] and Bernard et al.[6]

RESULTS

For the principal study on hoods, Table II provides the mean and standard deviations of the metabolic rate and

TABLE II. Normalized Metabolic Rate and Critical WBGT for Particle Barrier and Vapor Barrier Ensembles with and Without Hoods

	Normalized Metabolic Rate (W/m^2)		Critical WBGT (°C)		
	No Hood	Hood	No Hood	Hood	Difference
Tyvek 1427	181 ± 22	173 ± 34	34.1 ± 1.3	32.8 ± 2.6	1.3
Tychem QC	176 ± 27	177 ± 24	28.2 ± 2.9	27.1 ± 1.4	1.1
Combined ensembles	178 ± 24	175 ± 29	31.3 ± 3.7	29.9 ± 3.5	1.2[A]

[A]Discrepancy in differences between the means is due to one missing data point for each hood condition (n = 28 rather than 30 total). The value reported in the table is the difference in the least squares means from the general linear model analysis instead of the 1.4 between the two combined means.

critical WBGT data for the four combinations of ensemble and hood. A general linear model with two ensembles by two hood conditions and the interaction of ensemble and hood where the 15 participants were treated as a random effect was performed on metabolic rate to confirm that the work demands were not different among ensembles and conditions. There were no significant differences in normalized metabolic rate between ensembles ($p = 0.83$), between hood conditions ($p = 0.30$), or the interaction ($p = 0.45$).

Following a similar analysis for critical WBGT, there were main effects for ensemble ($p < 0.0001$) and for hoods ($p = 0.03$). There was no interaction ($p = 0.82$). The hooded ensembles had a lower critical WBGT than the nonhooded ensembles. The limited-use vapor barrier coveralls (Tychem QC) had a lower critical WBGT than limited-use, particle barrier coveralls (Tyvek 1427).

For the secondary study on flame-retardant fabrics, Table III provides the mean and standard deviation of the metabolic rate and critical WBGT for each ensemble. A general linear model with the three ensembles as the treatments using the 12 participants as a random effect was performed. There was no significant difference in normalized metabolic rate among ensembles ($p = 0.08$). For critical WBGT, there were no significant differences among ensembles ($p = 0.98$).

DISCUSSION

The evaluation of the effect of a hood integrated into the coverall configuration was based on the progressive heat stress protocol used to determine the critical WBGT. The difference in mean critical WBGT between a hooded configuration and one without a hood represented the effect of interest. A possible confounder in the experimental design was metabolic rate. Because there were no significant differences among the metabolic rates, they were considered to be adequately controlled. There were consistent differences between the hood/no-hood conditions for the two ensembles and no interaction. The difference for the particle barrier was 1.3°C WBGT and a little larger than the 1.1°C WBGT for the vapor barrier.

On the surface, this would suggest that the increase in evaporative resistance for the vapor barrier over the particle barrier was about 0.2°C WBGT and a small difference would be expected because the evaporative loss from the head is only 7%.[8] The direct evaporative loss from the head appeared to be small compared with the convective reduction in cooling from reduced air movement around the neck (to and from the microenvironment under the coveralls). That is, the change in the convection of water vapor around the head due to the hood was the dominant reason for the lower critical WBGT and, hence, lower evaporative cooling.

Because there was no interaction and the difference in the least squares means for the combined ensembles was about 1.2°C WBGT, this is the proposed WBGT clothing adjustment factor for adding a hood. There is no reason to believe that a hard hat or other form of head covering (e.g., respirator mask) would have nearly the same effect because it would not influence the convection of air around the neck like a hood would.

The critical WBGT was compared for two flame-retardant coveralls against work clothes at a targeted moderate metabolic rate of 180 W/m^2. Although there was not a statistical difference in metabolic rate among the three ensembles in the current study, the INDURA coveralls had a higher mean value by about 40 W/m^2, which could lead to a systematic lower critical WBGT. This might represent a practical difference. Bernard et al.[7] reported that the critical WBGT would change by -0.039°C $WBGT/W/m^2$; equating to an adjustment of 1.5°C WBGT in the authors' data if the metabolic rates were the same. Inspection of Table III shows no practical difference among the three ensembles for critical WBGT

TABLE III. Metabolic Rate and Critical WBGT for Cotton Work Clothes and Flame- Retardant Coveralls

	Normalized Metabolic Rate (W/m^2)	Critical WBGT (°C)
Work clothes (n = 15)	186 ± 31	33.9 ± 1.6
INDURA coveralls (n = 6)	220 ± 59	34.0 ± 0.7
Nomex coveralls (n = 6)	177 ± 16	33.9 ± 0.7

TABLE IV. WBGT-Based Clothing Adjustment Factors

Ensemble	Clothing Adjustment Factor (°C WBGT)
Work clothes	—
Cotton coveralls[6,7]	0
Flame-retardant coveralls (INDURA and Nomex)	0
Tyvek coveralls without hood[7]	1
Tyvek coveralls with hood	2
NexGen coveralls without hood[7]	2
Limited-use vapor barrier without hood[6]	10
Limited-use vapor barrier with hood	11

Note: Adjustment factors based on data from USF studies.

and, thus, no practical difference in the level of heat stress associated with the flame-retardant clothing. If the bias due to metabolic rate was considered, then the results would suggest that the INDURA coveralls had less heat stress than work clothes, which seems unlikely. In comparing flame-retardant shirt (Zirpo wool) and FR8 denim pants to work clothes, Cortes-Vizcaino and Bernard[9] reported an average difference of about 0.5°C WBGT and no significant difference for four participants at two levels of metabolic rate (similar difference of 75 W or about 40 W/m^2).

With that said, there is no *a priori* reason to argue that the level of heat stress associated with INDURA would be different from work clothes. There was also no difference in heat stress between Nomex coveralls and work clothes. Because there was no cross-over of participants and the number of observations was smaller than for any other recent studies, the conclusion is weaker than other recent data from USF[6,7] and about that reported earlier.[5] There was little reason to believe that INDURA or Nomex coveralls should be treated differently from work clothes; that is, the clothing adjustment factor is 0.

The current USF recommendations for some clothing ensembles are provided in Table IV. Work clothes are zero because they represent the baseline ensemble. From the previous and current studies, woven coveralls of cotton, INDURA, and Nomex do not add to the heat stress level, and WBGT adjustments were 0. In Table IV, cotton and flame-retardant ensembles are grouped individually, but the two flame-retardant ensembles are combined. Although Tyvek 1427 is no longer available, Tyvek coveralls are well represented by an adjustment of 1°C WBGT,[7] and the addition of hoods adds an additional 1°C WBGT. NexGen was added to the list to represent a specific microporous coverall with an adjustment of 2.5°C WBGT. Although not included in the table, the configuration with a hood should have been an adjustment of 3.5°C. Generically, Tychem QC represented any limited-use vapor barrier. For the coverall configuration without hood, the previously recommended value was 10°C WBGT,[6] and with a hood this would increase to 11°C.

ACKNOWLEDGMENTS

The authors would like to thank the participants and laboratory support, including Christina Luecke. This research was supported by a grant from the National Institute for Occupational Safety and Health.

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