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Heat stress risk profiles for three non-woven coveralls

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ABSTRACT

The ACGIH® Threshold Limit Value® (TLV®) is used to limit heat stress exposures so that most workers can maintain thermal equilibrium. That is, the TLV was set to an upper limit of Sustainable exposures for most people. This article addresses the ability of the TLV to differentiate between Sustainable and Unsustainable heat exposures for four clothing ensembles over a range of environmental factors and metabolic rates (M). The four clothing ensembles (woven clothing, and particle barrier, water barrier and vapor barrier coveralls) represented a wide range of evaporative resistances. Two progressive heat stress studies provided data on 480 trials with 1440 pairs of Sustainable and Unsustainable exposures for the clothing over three levels of relative humidity (rh) (20, 50 and 70%), three levels of metabolic rate (115, 180, and 254 Wm^{-2}) using 29 participants. The exposure metric was the difference between the observed wet bulb globe temperature (WBGT) and the TLV. Risk was characterized by odds ratios (ORs), Receiver Operating Characteristic (ROC) curves, and dose-response curves for the four ensembles. Conditional logistic regression models provided information on ORs. Logistic regressions were used to determine ROC curves with area under the curve (AUC), model the dose-response curve, and estimate offsets from woven clothing. The ORs were about 2.5 per 1°C-WBGT for woven clothing, particle barrier, and water barrier and for vapor barrier at 50% rh. When using the published Clothing Adjustment Values (CAVs, also known as Clothing Adjustment Factors, CAFs) or the offsets that included different values for vapor barrier based on rh, the AUC for all clothing was 0.86. When the fixed CAVs of the TLV were used, the AUC was 0.81. In conclusion, (1) ORs and the shapes of the dose-response curves for the nonwoven coveralls were similar to woven clothing, and (2) CAVs provided a robust way to account for the risk of nonwoven clothing. The robust nature of CAV extended to the exclusion of different adjustments for vapor barrier by rh.

KEYWORDS
CAV; clothing; exposure limit; heat stress; WBGT

Introduction

The wet bulb globe temperature (WBGT) has been used for over 60 years to limit exposures to heat stress.[1-7] The basic premise of occupational exposure limits to heat stress based on WBGT is that the heat stress is limited to a level at which most people will be able to sustain thermal equilibrium for hours with the assumption that this minimizes the risk for heat stroke in particular and exertional heat-related disorders in general. As a case definition, Sustainable exposures are heat stress levels at which thermal equilibrium can be maintained for extended periods, and Unsustainable exposures occur when there is a steady increase in heat storage due to an inability to maintain thermal equilibrium.[4] The ACGIH® (previously known as the American Conference of Governmental Industrial Hygienists) Threshold Limit Value® (TLV®) for heat stress and strain uses the WBGT with thresholds adjusted for metabolic rate (M), and clothing.[1] Clothing is accounted for with Clothing Adjustment Values (CAVs are also known as Clothing Adjustment Factors, CAFs). Adjusting a WBGT-based threshold for different clothing ensembles has a long history.[8–12] Using current methods to determine CAV, the first step was to find a threshold WBGT (critical WBGT, $WBGT_{crit}$) between Sustainable and Unsustainable heat stress for a given metabolic rate and clothing ensemble.[8,9] The average $WBGT_{crit}$ for work clothes was the reference point. The difference between the reference point and the average $WBGT_{crit}$ for the test ensemble was the CAV for that ensemble. For three coveralls made from non-woven fabrics reported in two studies,[8,9] the CAV was generally independent of the relative humidity (rh), except for

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vapor-barrier coveralls.[9] The CAV was also independent of the M.[8] The CAVs were related to the apparent evaporative resistances.[13]

Recently, the profile for the transition from Sustainable to Unsustainable heat stress exposures while wearing woven clothing (cotton work clothes or cotton coveralls) was described and the ability of the TLV to distinguish between Sustainable and Unsustainable was determined.[4] The probability of an Unsustainable exposure for an individual based on the elevation above the TLV, referred to as ΔTLV, was $p = e^{(-4.77 + 0.78\ \Delta TLV)} / (1 + e^{(-4.77 + 0.78\ \Delta TLV)})$. Graphically, this curve looks like an idealized dose-response relationship. At the TLV ($\Delta TLV = 0$), the model probability of being Unsustainable was 1%. The odds of being Unsustainable was the probability (p) of being Unsustainable divided by the p of being Sustainable (1-p) for a given exposure (i.e., ΔTLV). The odds ratio (OR), which is the ratio of the odds at one exposure divided by the odds at a reference exposure, was 2.5/°C-WBGT. In this case, the dose-response curve and the OR represents a heat stress risk profile for woven clothing based on ΔTLV.

The receiver operating characteristic curve (ROC curve) describes the relationship between the sensitivity and 1-specificity of ΔTLV at any given threshold. As the value of ΔTLV increases, the sensitivity decreases and the specificity increases. The area under the ROC curve (AUC) describes the overall ability of the metric to distinguish Unsustainable from Sustainable exposures. Ideally, the AUC would be 1.0, and random chance would be 0.5. The AUC provides an opportunity to compare alternative metrics. The AUC for ΔTLV for woven clothing was 0.85.[4]

This article extended the previous research on woven clothing[4] to examine the risk profiles of three nonwoven clothing ensembles. While the nonwoven coveralls were a convenience sample, they represent similar construction with different fabric characteristics over the range of clothing covered by the TLV. That is, it addressed the ability of the ACGIH® TLV® to differentiate between Sustainable and Unsustainable heat exposures for four clothing ensembles over a range of environments and metabolic rates. The objectives were (1) to characterize the risk profile for three nonwoven coveralls with widely different evaporative resistances in comparison to woven clothing, and (2) to examine the ability of CAVs to account for the contribution of non-woven fabrics to heat stress exposure.

Methods

The data used for this article were taken from two previous studies at USF,[8,9] which were approved by the USF institutional review board. The progressive heat stress protocol used in these studies began with comfortable environments already described that were easily compensable. After thermal equilibrium was established, the temperature and water vapor pressure were slowly increased in 5-min intervals at constant rh and the steps were designed to establish a quasi-steady-state physiological response for each step increase in heat load. Rectal temperature (T_{re}), heart rate (HR), skin temperature (T_{sk}), and ambient conditions were monitored continuously and recorded every 5 min. Metabolic rate was estimated from the assessment of oxygen consumption via expired gases sampled with a Douglas bag every 30 min in a trial. The transition from a steady value for T_{re} to values that were steadily increasing were marked as the critical condition. A compensable point where the individual clearly could maintain thermal equilibrium was selected as 15 min before the critical condition; and an uncompensable point where the individual clearly could not maintain thermal equilibrium was selected as 15 min after the critical condition (see Figure 1, which was taken from a previous publication[4]). The 15-min period before and after the critical condition was selected to be near the critical condition to minimize the difference in WBGT but with high confidence that the characterizations of compensable and uncompensable were correct.[4]

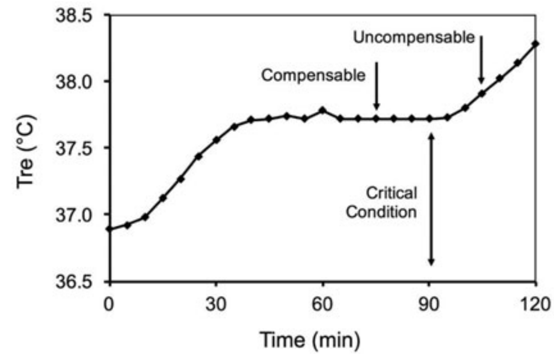

Figure 1. The time course of T_{re} for an example trial with arrows to indicate the critical condition, the compensable condition established 15 min before the critical condition, and uncompensable 15 min after it.[4]

There were 480 trials for each of the 29 participants. One USF study[9] used a progressive heat stress protocol to find the rh on $WBGT_{crit}$ for five clothing ensembles that included work clothes (140 g m^{-2} cotton shirt and 270 g m^{-2} cotton pants), and cotton coveralls (310 g m^{-2}) plus three nonwoven protective clothing coveralls. The nonwoven coveralls were characterized as (1) particle-barrier (Tyvek® 1424 and 1427; similar to Tyvek 1422A); (2) water-barrier, vapor-permeable (NexGen LS 417; microporous membrane); and (3) vapor-barrier (Tychem QC, polyethylene-coated Tyvek). The target M was 160 W m^{-2} to approximate moderate work performed on a level

Table 1. Physical characteristics (mean ± standard deviation) of participants.

	N	Age [yr]	Height [cm]	Weight [kg]	Body Surface Area [m^2]
Relative Humidity Study[9]					
Men	9	29 ± 6.8	183 ± 6	97 ± 19	2.18 ± 0.20
Women	5	32 ± 9.1	161 ± 7	64 ± 17	1.66 ± 0.23
Metabolic Rate Study[8]					
Men	11	28 ± 10	176 ± 11	82 ± 12	1.98 ± 0.47
Women	4	23 ± 5	165 ± 6	64 ± 18	1.70 ± 0.22
Pooled					
Men	20	29 ± 9	179 ± 34	89 ± 23	2.07 ± 0.41
Women	9	28 ± 8	163 ± 7	64 ± 17	1.74 ± 0.29

treadmill, at three levels of relative humidity: warm humid at 30°C and 70% rh; hot dry, at 40°C and 20% rh; and a midrange of 34°C with rh of 50%. The other USF study[8] used a progressive heat stress protocol to evaluate the five ensembles described above, but assessed the effects of varying M at a rh of 50%. The three target Ms on a level treadmill were 115, 175, and 250 W m^{-2} to approximate light, moderate, and heavy work.

The characteristics of the 29 participants who took part in these trials are summarized in Table 1. All participants were acclimatized by 2-hr exposures over five successive days to dry heat (50°C and 20% rh) at 160 W m^{-2} while wearing shorts and tee shirt.

Because no differences in $WBGT_{crit}$ and apparent total evaporative resistance were found between work clothes and cotton coveralls in previous studies,[8,9,13] these trials were combined under the category of woven clothing. There were 176 trials for woven cotton clothing over the two studies. The number of trials for the nonwoven coveralls were 119 for particle barrier, 91 for water barrier, and 94 for vapor barrier (see Table 2) (15 at 20% rh, 64 at 50% rh, and 15 at 70% rh).

The present study had a crossover design within a trial; and each individual served as their own control across fabric types; thus, observations on individuals were dependent observations. Within a trial, the observation 15 min after the critical condition (uncompensable) was classified as Unsustainable and the observation 15 min prior to the critical condition was classified as Sustainable (compensable). The critical condition was classified as Sustainable if T_{re} was less than 38°C or if the change in T_{re} was less than or equal to 0.1°C over the preceding 20 min. The critical condition was classified as Unsustainable if T_{re} was greater than or equal to 38°C and if the change in T_{re} increased by more than 0.1°C over the preceding 20 min.[4] The investigation's outcome was Unsustainable (case) vs. Sustainable (control). For each trial, there were two pairs of Sustainable-Unsustainable observations. The case status was the dependent variable, and the independent heat stress exposure metric was the difference between the observed WBGT and the TLV value, which was adjusted for M.[4] That is, TLV = 56.7 – 11.5 * $\log_{10}$ (M);[1]; and the metric was $\Delta TLV = WBGT_{observed} - TLV$.[4]

Using ΔTLV as the predictor, the effect of clothing on the OR for each of the clothing types was examined with conditional logistic regression models to account for the dependent nature of the data. Because an interaction between vapor barrier and relative humidity was found for the CAVs,[9] the OR for each combination of vapor barrier and rh was also determined.

In a parallel approach, logistic regression using only the critical condition (transitions at $WBGT_{crit}$) data was used on each of the clothing types and with vapor barrier at three levels of rh to model a dose-response curve. For each clothing type and for vapor barrier by rh (seven models altogether), the data were rank ordered from the lowest to highest ΔTLV. Then the odds were estimated for each observation of ΔTLV as the number of trial critical conditions at or below the ΔTLV divided by the number of observations above the ΔTLV. Finally, the logistic regression was computed as the ln(odds) = a + b ΔTLV.

To examine the CAV as a means to account for clothing in the TLV exposure limit, the adjustment was added to the ΔTLV value. The ROC curve was determined for the complete pool of data (three observations per trial that included the compensable, $WBGT_{crit}$, and uncompensable observations).

Table 2. Number of observations as Sustainable and Unsustainable overall and by fabric type, and the associated number of trials.

	All	Woven	Particle Barrier	Water Barrier	Vapor Barrier
Sustainable	728	273	184	131	140
Unsustainable	712	255	173	142	142
Trials	480	176	119	91	94

Results

Table 2 provides the number of observations corresponding to Sustainable and Unsustainable conditions, as well as the number of trials, which was one third of the total observations.

From the conditional logistic regressions, Table 3 reports the ORs with 95% confidence intervals (CI) for the association between ΔTLV and the outcome of Unsustainable. There was insufficient data for the conditional logistic regressions for the combinations of vapor barrier at 20 and 70% rh. The table also reports the results of the logistic regression models.

Figure 2 illustrates the critical data and the associated logistic regression models. Because there were large differences for vapor barrier among the three rh levels, the

Table 3. Odds ratios and 95% confidence intervals (CI) from the conditional logistic regression models and the logistic regression models.

Ensemble	Odds Ratio CI	Logistic Regression Model ln[p/(1-p)]
Woven Clothing	2.47 2.12 – 2.88	$= -4.70 + 0.767\ \Delta TLV$
Particle Barrier	2.40 2.00 – 2.88	$= -4.16 + 0.744\ \Delta TLV$
Water Barrier	2.74 2.15 – 3.50	$= -3.40 + 0.816\ \Delta TLV$
Vapor Barrier (pooled)	1.77 1.53 – 2.04	$= 0.523 + 0.672\ \Delta TLV$
Vapor Barrier at 20% rh	—	$= 3.95 + 0.888\ \Delta TLV$
Vapor Barrier at 50% rh	2.42 1.84 – 3.18	$= 0.309 + 0.834\ \Delta TLV$
Vapor Barrier at 70% rh	—	$= -1.18 + 1.02\ \Delta TLV$

Table 4. Clothing Adjustment Values (CAV,°C-WBGT) adapted from previous articles, the value of ΔTLV at a probability of Unsustainable of 0.5 (ln(odds) = 0), and the difference in ΔTLV from woven clothing.

Ensemble	CAV from USF Studies (8, 9)	CAV from TLV (1)	ΔTLV at ln(odds) = 0	Difference from Woven Clothing
Woven Clothing (reference value)	0	0	6.1	0.0
Particle Barrier	0.7	1	5.6	0.5
Water Barrier	2.2		4.2	2.0
Vapor Barrier (pooled)	7.7	11	− 0.8	6.9
Vapor Barrier at 20% rh	11.4		− 4.4	10.6
Vapor Barrier at 50% rh	7.8		− 0.4	6.5
Vapor Barrier at 70% rh	5.4		1.2	5.0

combinations of vapor barrier and rh are presented in the figure.

Table 4 summarizes the previously published CAVs findings from USF[8,9] and the ACGIH® TLV[1] for woven clothes and three nonwoven ensembles. The mid-point on the dose-response curves would be the ΔTLV at a probability for Unsustainable of 0.5 (the value of ΔTLV at ln(odds) = 0). Using the woven clothing as the reference, the characteristic difference for each clothing type would be the difference in ΔTLV. These values are also reported in Table 4.

The ROC curve provided insight into the ability to discriminate between Sustainable and Unsustainable heat stress exposures.[4] The ROC curves for three observations per trial across all trials was determined where ΔTLV was adjusted for clothing using three different sets of adjustment values reported in Table 4: (1) the CAV from previous USF data;[8,9] (2) the published CAV from the ACGIH® TLV®,[1] which does not have a value for water barrier; and (3) the difference in ΔTLV at p = 0.5. The ROC curves for all fabric types with vapor barrier adjustments for rh based on the USF values in Table 4 and for woven clothing, particle barrier and vapor barrier fabrics based on the TLV are shown in Figure 3. The AUCs were 0.86 for USF CAVs and 0.81 for TLV CAVs. There was no difference in AUC to two significant places between the USF adjustment values and those derived from the differences in the dose-response curves (0.864 vs. 0.866). Looking at just the vapor barrier clothing with a CAV = 11°C-WBGT, the AUC was 0.87.

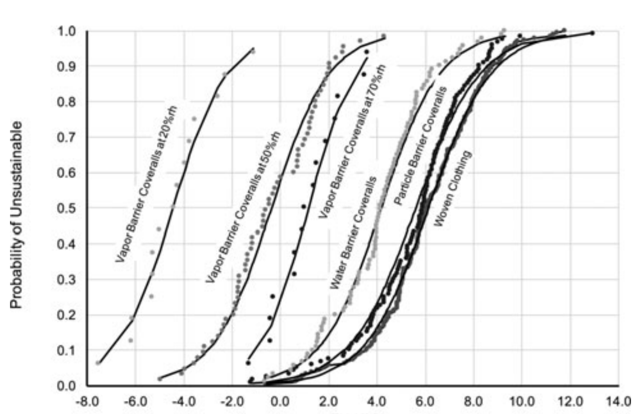

Figure 2. Risk profiles for three clothing types and vapor barrier by three levels of relative humidity.

Discussion

The data used in this article represented four types of clothing at three levels of M (nominally 115, 175, and 250 W m^{-2} to approximate light, moderate, and heavy

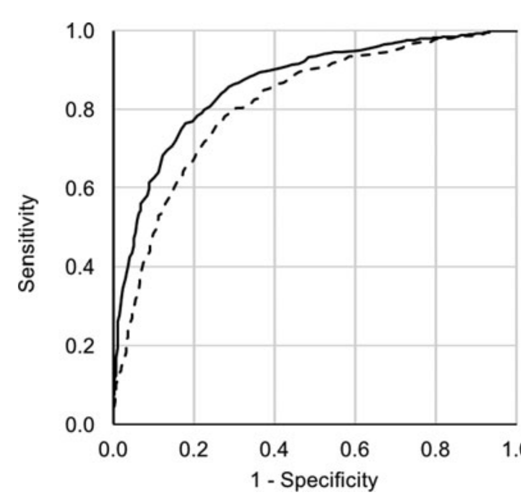

Figure 3. The Receiver Operating Characteristic (ROC) curves after adjusting for USF CAV for all four clothing fabrics with vapor barrier adjusted for relative humidity (solid line) and with fixed values from TLV for particle barrier (1°C-WBGT) and vapor barrier only (11°C-WBGT) (dashed line). The areas under the curve (AUC) are 0.86 and 0.81, respectively.

work with a range from 170–500 W) and three levels of rh (20, 50, and 70%). The spread between the compensable WBGT and the $WBGT_{crit}$ and between $WBGT_{crit}$ and Uncompensable WBGT was about 3°C-WBGT, which was a relatively narrow range around the transition from Sustainable to Unsustainable conditions. Roughly one half of the observations were Sustainable and the other half Unsustainable, so that there was a good balance between cases and controls. Overall, the dataset represents a broad range of occupational exposures near the occupational exposure limit represented by the ACGIH® TLV.[1]

The four clothing ensembles had substantially different apparent total evaporative resistances of 0.013 m^2 kPa W^{-1} for woven clothing, 0.015 m^2 kPa W^{-1} for particle barrier, 0.018 m^2 kPa W^{-1} for water barrier, and 0.032 m^2 kPa W^{-1} for vapor barrier.[13] With CAVs of 0, 1, 2, and 5–11°C-WBGT, the clothing ensembles represent a wide range of WBGT-based CAVs. The actual ensembles were chosen as a convenience sample because the investigators had extensive data on each of them under conditions described in the previous paragraph.

The factor that describes the risk profile is the OR. Based on conditional logistic regressions reported in Table 3, the ORs for the fabric types were consistent for woven, particle barrier, and water barrier pooled across three levels of M and three levels of rh and for vapor-barrier across three levels of M at 50% rh. There was insufficient data for vapor barrier at 20% and 70% rh to do a conditional logistic regression. The ORs ranged from 2.4–2.7 and well within the CI for each of the estimates. An OR of 2.5/1°C-WBGT appeared to be a fair representation of the overall risk for Unsustainable.

The CAVs for vapor barrier fabric at three rh levels was reported earlier[9] and seen in Table 4. When all the vapor barrier data were pooled to calculate the OR, the estimate was 1.8, which was less than the other three fabric types. This difference provided further evidence for the effect modification for vapor barrier fabrics due to humidity. The OR increased from 1.8 to 2.4 when only the 50% rh data were used, which provided some support for the effect of rh.

Another characteristic of the risk profile is the dose-response curve. To illustrate the dose-response relationship, only the transition data at the critical condition were used (i.e., $WBGT_{crit}$). The data were modeled with logistic regression based on the estimated odds from rank ordering the data. These models are provided in Table 3 and illustrated in Figure 2 with the data. As expected from the ORs, the curves for each clothing type were similar in shape. The logistic regression (unlike the conditional logistic regression) provided an intercept that offsets the curves. As expected from the CAV studies based on ANOVAs,[8,9] the particle barrier was close to the woven clothing with the water barrier farther to the left. Because vapor barrier interacted with rh, there were three curves to represent vapor barrier.

CAVs were based on the idea that the effective exposure could be characterized as the ambient WBGT plus the effect of clothing expressed in units of°C-WBGT.[1,8-12] The values were developed from professional judgement,[12] assessment of lower percentiles,[10] and mean values.[8,9,11] Table 4 summarizes published values from the same USF data used in this study but based on analysis of variance of the mean data in fixed categories. Alternatively, the offsets of the dose-response curves were determined from the model-based central probability of Unsustainable and reported in the last column of Table 4. It was clear that the values were similar, and within 1°C-WBGT of each other. That is, different approaches on the same data yielded similar results. The similar curves provide support for the idea that the CAV was not only descriptive of the mean difference but is representative of a range of critical exposures due to individual differences in heat tolerance.

Finally, the use of exposure adjustments due to clothing was inspected via the ability to discriminate Sustainable and Unsustainable. The ROC AUC for woven clothing was reported previously as 0.85.[4] When the six fabric conditions (woven, particle barrier, and water barrier plus vapor barrier at the relative humidity levels) were adjusted by the USF CAV or the offsets reported in Table 4, the ROC was 0.86, which was virtually the same as for woven clothing alone. Again, this demonstrated that the CAVs for specific clothing (adjusted further for rh for vapor barrier) were robust. Using the ACGIH® TLV® CAVs including the high-end adjustment of 11°C-WBGT for vapor barrier, the AUC dropped to 0.81, which was expected but still good.

One limitation on the estimation of the ORs was the nature of the progressive heat stress protocol. While the three observations had a high degree of certainty for classification of Sustainable and Unsustainable, there was a bias toward increasing exposure levels going from compensable through the critical point to uncompensable. In a different exposure assessment protocol such as that used by Lind,[5] there may be a random decrease in exposure level in some observations that would lower the estimated OR using conditional logistic regression. The ORs from the logistic regressions for woven, particle barrier and water barrier fabrics and vapor barrier at 50% relative humidity were 2.1–2.4, which were a little lower and probably reflect the lower boundary for the ORs.

A second caution relates to the absence of knowing a threshold for evaporative resistance above which the effects of humidity become important. For an apparent total evaporative resistance (based on wear trials and not manikin data[13]) below 0.016 m^2 kPa W^{-1}, there was no effect but there was one at 0.032 m^2 kPa W^{-1}. It is worthwhile exploring how apparent evaporative resistances above 0.015 m^2 kPa W^{-1} play out with respect to changes in humidity.

The principal purpose of this article is to characterize the risk of selected ensembles and demonstrate an overall approach. A final caution is the care in generalizing the information beyond the selected ensembles. At present, the risk characterization of the nonwoven fabrics is based on a consistent construction of the coveralls in a single-layer configuration without hoods and closures at the wrists and ankles, with the only difference being the evaporative resistance of the fabric. To the extent that other clothing configurations and fabrics are similar to the test ensembles in apparent total evaporative resistance, the more likely the observations can be extended to them.

This article's novelty is that it extends the information on risk profiles from woven clothing to a range of nonwoven fabrics. Overall, the risk profiles for nonwoven clothing worn as coveralls were similar in the rate of change of risk (OR about 2.5/°C-WBGT). With woven clothing as the reference, the probability curves (Figure 2) shifted progressively to the left in the order of increasing evaporative resistance (i.e., particle barrier, water barrier, and vapor barrier) with offset values similar to the previously determined CAVs. The vapor barrier fabric demonstrated an interaction with rh for apparent total evaporative resistance and this interaction was seen in the separate probability curves. Further, the use of CAVs provided a robust way to account for the risk of nonwoven clothing on the transition from Sustainable to Unsustainable. The robust nature extended to the exclusion of different adjustments for vapor barrier by rh. The interaction between evaporative resistance and humidity required further exploration.

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Disclaimer

The authors declare no conflict of interest relating to the material presented in this article. Its contents, including any opinions and/or conclusions expressed, are solely those of the authors.

One of the authors [TEB] has acted as an expert witness for both private companies and OSHA in litigation concerning heat stress exposures and may in the future serve as an expert witness in court proceedings related to heat stress.

The mention of trade names was to provide specifics about the clothing and do not represent an endorsement by the authors.

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