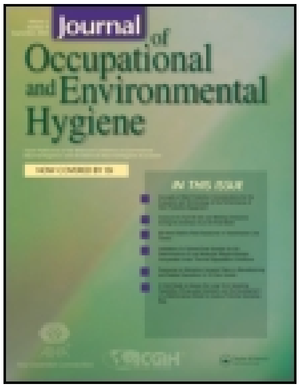

Journal of Occupational and Environmental Hygiene
Publication details, including instructions for authors and subscription information:
http://oeh.tandfonline.com/loi/uoeh20

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Accepted author version posted online: 30 Oct 2013.Published online: 30 Oct 2013.

To cite this article: Jung-Hyun Kim , Jeffery B. Powell , Raymond J. Roberge , Angie Shepherd & Aitor Coca (2014) Evaluation of Protective Ensemble Thermal Characteristics Through Sweating Hot Plate, Sweating Thermal Manikin, and Human Tests, Journal of Occupational and Environmental Hygiene, 11:4, 259-267, DOI: 10.1080/15459624.2013.858820

To link to this article: http://dx.doi.org/10.1080/15459624.2013.858820

Journal of Occupational and Environmental Hygiene, 11: 259–267
ISSN: 1545-9624 print / 1545-9632 online
DOI: 10.1080/15459624.2013.858820

Evaluation of Protective Ensemble Thermal Characteristics Through Sweating Hot Plate, Sweating Thermal Manikin, and Human Tests

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The purpose of this study was to evaluate the predictive capability of fabric Total Heat Loss (THL) values on thermal stress that Personal Protective Equipment (PPE) ensemble wearers may encounter while performing work. A series of three tests, consisting of the Sweating Hot Plate (SHP) test on two sample fabrics and the Sweating Thermal Manikin (STM) and human performance tests on two single-layer encapsulating ensembles (fabric/ensemble A *= low THL and* B *= high THL), was conducted to compare THL values between SHP and STM methods along with human thermophysiological responses to wearing the ensembles. In human testing, ten male subjects performed a treadmill exercise at 4.8 km and 3% incline for 60 min in two environmental conditions (mild = 22°C, 50% relative humidity (RH) and hot/humid = 35°C, 65% RH). The thermal and evaporative resistances were significantly higher on a fabric level as measured in the SHP test than on the ensemble level as measured in the STM test. Consequently the THL values were also significantly different for both fabric types (SHP vs. STM: 191.3 vs. 81.5 W/m^2 in fabric/ensemble* A*, and 909.3 vs. 149.9 W/m^2 in fabric/ensemble* B *($p < 0.001$). Body temperature and heart rate response between ensembles* A *and* B *were consistently different in both environmental conditions ($p < 0.001$), which is attributed to significantly higher sweat evaporation in ensemble* B *than in* A *($p < 0.05$), despite a greater sweat production in ensemble* A *($p < 0.001$) in both environmental conditions. Further, elevation of microclimate temperature ($p < 0.001$) and humidity ($p < 0.01$) was significantly greater in ensemble* A *than in* B*. It was concluded that: (1) SHP test determined THL values are significantly different from the actual THL potential of the PPE ensemble tested on STM, (2) physiological benefits from wearing a more breathable PPE ensemble may not be feasible with incremental THL values (SHP test) less than approximately 150–200 W·m^2, and (3) the effects of thermal environments on a level of heat stress in PPE ensemble wearers are greater than ensemble thermal characteristics.*

Keywords total heat loss, thermal resistance, vapor permeability, core temperature, evaporative heat loss

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INTRODUCTION

There are over 1 million firefighters, 500,000 EMS personnel, and 39,000 HazMat responders who use personal protective equipment (PPE) ensembles occupationally in the public service sector of the United States.[(1)] While effectively protecting wearers from physical contact with toxic chemical and environmental hazards, a PPE ensemble itself impedes heat exchange between the body and environment and thus increases thermal stress on the wearer, leading to a decrement in physical performance capabilities and increased risk of heat stress-related injuries.[(2–6)]

The heat transfer ability of PPE ensemble material is commonly determined by the Sweating Hot Plate (SHP) test in accordance with either ASTM International (ASTM) or International Organization for Standardization (ISO) standards.[(7,8)] Although differing slightly in the test conditions and measurement parameters, fundamental aspects of the standards are identical in that SHP simulates dry heat and moisture transfer from a flat-heated metal plate (i.e., representing the skin surface) through a layer(s) of small representative fabric (i.e., representing the clothing barrier) to the environment under tightly controlled ambient temperature, relative humidity, and air velocity. Thus, thermal and evaporative resistance of a fabric is measured and SHP test results, expressed in Total Heat Loss (W/m^2), have been shown to be reproducible and repeatable when the test procedures are followed correctly.[(9,10)] However, there exists a general understanding that thermal characteristics of a fabric, determined by the means of SHP test, are not directly applicable to a whole clothing system or heat exchange between the clothed human body and environment.

This is because a number of other clothing parameters (e.g., fit, seams, area factor, insulating air layers, design, reinforcements, and so on) and human factors (e.g., body surface area, metabolic heat production, uneven distribution of skin temperatures, and so on) are known to influence the human-environment heat transfer characteristics.

The National Fire Protection Association (NFPA), nonetheless, has established THL requirements for the performance configuration of various PPE ensembles that are determined by the SHP test method specified in Part C of ASTM F1868,(7) where higher THL values indicate a greater heat transfer capability of the fabric. For example, the minimum THL requirements are 200 W/m^2 for a Class-3 Chemical Biological Radiological and Nuclear (CBRN) ensemble,(11) 205 W/m^2 for a structural firefighting ensemble,(12) 250 W/m^2 for a CBRN ensemble for technical rescue,(13) 450 W/m^2 for rescue/recovery and wildland firefighting ensembles, Class-4 CBRN and emergency medical ensembles,(11,13–15) and 650 W/m^2 for utility ensemble for technical rescue.(13) However, the thermophysical and physiological basis for the given THL values of various PPE performance standards are not provided, apart from the concerns of THL applicability to a clothing system. Furthermore, there is a lack of other alternative test batteries for the standards, such as thermal manikin and/or human performance tests, which would provide more comprehensive health hazard assessment in relation to PPE ensemble thermal stress.(16)

To rectify the disconnect between the standards given at the fabric level and the actual thermal stress of the entire PPE ensemble, the present study aimed to evaluate the predictive capability of fabric THL values on human thermophysiological responses to wearing PPE ensembles. For this purpose, three steps of heat stress evaluation on PPE ensembles were carried out, which include the SHP test on the ensemble fabric, sweating thermal manikin (STM) test on the complete PPE ensemble, and laboratory human testing on the complete PPE ensemble in two different environmental conditions. Considering the availability and cost for PPE ensemble material and construction, two types of protective fabrics that meet the lowest and highest THL requirements ($\geq$ 200 and 650 W/m^2) criteria within NFPA standards were evaluated in the present study.

METHODS

Sweating Hot Plate (SHP) Test

Two single-layer fabrics, with a pre-determined THL value of approximately 200 W/m^2 (Fabric *A*) and 900 W/m^2 (Fabric *B*), were provided by a manufacturer of protective fabrics (W.L. Gore & Associates, Inc., Elkton, Md.). These fabrics, designed to be semi-permeable barrier fabrics, are commercially available on the market and have been used to construct PPE ensembles in various applications.

To confirm the manufacture-provided THL values of the fabrics, the SHP test was conducted at Underwriters Laboratories (Research Triangle Park, N.C.) in accordance with the procedures in ASTM F1868(7); Part C-Total Heat Loss in a Standard Environment (25°C, 65% RH). The fabric specimens tested were 20 × 20 inches in size and underwent pre-test conditioning procedures (e.g., smoothing, pressing) to fully cover the surface of the SHP without undesirable wrinkles, which may affect the test results. All measurements were triplicated with three specimens of each fabric, and additional specimens were tested if the individual test results were not within 10% of the average values as per the standard. For the test results, average intrinsic thermal resistance (K·m^2/W), average apparent intrinsic evaporative resistance (kPa·m^2/W), and THL (W/m^2) values are reported (Table I).

Sweating Thermal Manikin (STM) Test

Test ensembles (ensembles *A* and *B*) were constructed from fabrics *A* and *B* using a garment design that is identical to the commercially available CBRN ensemble (Model: Extended Response Suit, Lion Apparel, Dayton, Ohio). The CBRN ensemble is a one-piece coverall with attached glove liners and booties that encapsulate a wearer's whole body except a frontal face area for a respiratory protective facemask, and

TABLE I. Summary of Thermal Characteristics of the Study Fabric and Ensemble Through Sweating Hot Plate and Sweating Thermal Manikin Testing

Specimen	Average intrinsic thermal resistance (K·m^2/W)	Average apparent intrinsic evaporative resistance (kPa·m^2/W)	Average total heat loss (W/m^2)
Fabric ***A***	0.0186 (0.0009)†	0.1702 (0.0082)†	191.3 (1.8)^{A†}
Fabric ***B***	0.0048 (0.0003)‡	0.0017 (0.0)‡	909.3 (3.4)^{A‡}
Ensemble ***A***	0.1495 (0.0046)†	0.4779 (0.0214)†	81.5 (1.8)^{B†}
Ensemble ***B***	0.1340 (0.0012)‡	0.0411 (0.0009)‡	149.9 (2.1)^{B‡}

Notes: Values are mean (SD). Symbols (A = †, B = ‡) denote a statistical difference ($p < 0.001$) in comparison within the same fabric and ensemble type.

^{A}Total heat loss for a 25°C, 65% RH environment calculated as $THL = [10°C \cdot (R_{cf} + 0.04)^{-1}] + [3.57\ kPa \cdot (R^{A}_{ef} + 0.0035)^{-1}]$, where R_{cf} (Average intrinsic thermal resistance) and R^{A}_{ef} (Average apparent intrinsic evaporative resistance).

^{B}Total heat loss for a 20°C, 40% RH environment calculated as $THL = [(Ps - Pa) \cdot R_{et}^{-1}] + [(Ts - Ta) \cdot R_{t}^{-1}]$, where Ps (water vapor pressure at the surface of the manikin; kPa), Pa (water vapor pressure in the ambient; kPa), Ts (temperature at the manikin surface; °C), Ta (ambient temperature; °C), R_{et} (total evaporative resistance of the ensemble and surface air layer; kPa·m^2/W), and R_t (total thermal resistance of the ensemble and surface air layer; K·m^2/W).

are accompanied by outer gloves and chemical-resistant rubber boots. Medium-size ensembles were tested in the actual configuration, with the exception of the respiratory protective facemask being replaced by a spirometer mask to obtain cardiopulmonary data during human testing.

The measurements of thermal and evaporative resistance of ensembles *A* and *B* were conducted using a thermal sweating manikin (Model: Newton-34 sweating zones, Measurement Technology Northwest, Seattle, Wash.) at the Textile Protection and Comfort Center (North Carolina State University, Raleigh, N.C.). All measurements were triplicated with one PPE ensemble constructed from each fabric, and the testing was conducted in accordance with the standard procedure by ASTM International.[17,18]

Human Testing

Human subject testing on PPE ensembles *A* and *B* was conducted at the National Personal Protective Technology Laboratory (Pittsburgh, PA.) according to the standards reviewed and approved by National Institute for Occupational Safety and Health's (NIOSH's) Human Subjects Review Board.

Subjects

Ten healthy male subjects, who were cleared following a general health screening by a licensed physician and completed a graded exercise testing with a maximal oxygen uptake (VO_{2max}) greater than 50 ml·kg^{-1}·min^{-1}, participated in the present study. The anthropometric characteristics of the subjects were (mean ± standard deviation) age; 22.5 ± 3.0 years, height; 185 ± 5.0 cm, weight; 80.2 ± 7.9 kg, body surface area; 2.0 ± 0.1 m^2, and VO_{2max}; 58.6 ± 6.9 ml·kg^{-1}·min^{-1}. All subjects were given an orientation session to explain the purpose of the study and risks associated with performing the study protocol. Written informed consent was obtained prior to study participation.

Procedure

The subjects participated in four trials of ensemble testing (2 ensembles × 2 environmental conditions) after the completion of the ensemble familiarization. The ensemble familiarization included ensemble fit-testing, donning/doffing, and walking with boots. Only one ensemble test was performed on a given day, and each visit was separated by at least 48 hr to minimize any heat adaptation effect and to provide ample time for recovery. All trials of the testing were undertaken at the same time of day to minimize circadian rhythm effect on thermo-physiological responses, and the order of the four trials was randomized across the subjects.

The subjects were instructed to abstain from strenuous exercise, caffeine, and alcohol at least 24 hr prior to a scheduled test. Upon arrival at the laboratory, the subjects underwent a brief medical examination for vital sign check-up and provided a midstream urine sample to measure baseline hydration status using a urine specific gravity refractometer (Model: PAL-10S, Atago Co., Tokyo, Japan). The subjects then consumed 500 ml of water over an approximately 30-min period before entering an environmental chamber. Upon completion of the water ingestion, subjects entered the chamber, were weighed, and donned their assigned ensemble with assistance from researchers. The subjects were then seated quietly on a chair for stabilization (5–20 min; varied with each visit) and baseline physiological measurements while ambient temperature and humidity were maintained at 22°C and 30% RH, respectively.

Following the baseline measurements, the subjects performed a constant-pace treadmill exercise at 4.8 km/hr and 3% incline for 60 min either in a mild (22°C, 50% RH, 1.32 kPa) or hot/humid (35°C, 65% RH, 3.65 kPa) environmental condition. No direct radiant heat was present and the wind speed was maintained constant at 0.15 m·sec^{-1}. During the test, hydration was prohibited and the subjects were encouraged to complete the test unless any of the laboratory testing termination criteria were met. The termination criteria included rectal temperature (T_{re}) $\geq$ 39.5°C, heart rate (HR) $\geq$ 95% HR_{max} for more than 2 min, or volitional fatigue (rated perceived effort (RPE) $\geq$ 19), and the subject's desire to stop. When a subject was not able to complete testing, due to either volitional fatigue or desire to stop at a given PPE and environmental condition, he was asked to repeat the same test at the next visit. If the failure recurred, the subject was removed from study participation.

Measurements

T_{re} was measured for body core temperature monitoring, using a rectal thermistor (Model: REF-4491, YSI Temperature, Dayton, Ohio) inserted 13cm beyond the anal sphincter. Skin temperatures were measured using a 2.54 cm diameter T-type (copper/constantan) thermocouple, incorporating simultaneous measurements of heat flow (Concept Engineering, Old Saybrook, Conn.) attached onto 8 body sites with a transparent dressing film (Model: Tegaderm, 3M, St. Paul, Minn.). Area weighted mean skin temperature (T_{sk}) was calculated according to ISO-9886[19] as given in Equation 1 below.

$$\begin{aligned} T_{sk} = {} & 0.07\,(\text{forehead}) \times 0.175\,(\text{scapula}) \times 0.175\,(\text{upper chest}) \\ & \times 0.07\,(\text{upper arm}) \times 0.07(\text{forearm}) \times 0.05\,(\text{hand}) \\ & \times 0.19\,(\text{anterior thigh}) \times 0.2\,(\text{calf}) \qquad \textbf{(1)} \end{aligned}$$

PPE ensemble microclimate relative humidity (RH_{micro}) and temperature (T_{micro}) were also measured, using a combined humidity and temperature probe (Model: HMP110, Vaisala Inc., Woburn, Mass.) placed in a bulk space approximately at the waistline inside the ensemble. All thermoregulatory parameters were collected every 2 sec through a customized data acquisition system with LabVIEW software (V. 2009, National Instruments, Austin, Texas).

HR was continuously monitored using a Polar HR transmitter (Polar Electro Inc., Lake Success, N.Y.) strapped on the chest. Breath-by-breath pulmonary gas exchange was measured using a portable metabolic system (Model: K4b^2, COSMED, Rome, Italy) by which HR and gas exchange data were continuously monitored and stored wirelessly. Among various pulmonary parameters measured by the system, VO_2, carbon dioxide production (VCO_2), and the derived respiratory quotient (RQ) data were collected, being necessary for the calculation of heat exchange in the present study.

The subjects' pre and post-trial nude body weights were measured to the nearest 1 g on a calibrated scale (Model: Electronic scale-4450, GSE, Farmington Hills, Mich.) along with the measurement of weight change in underwear and PPE to determine evaporative and non-evaporative sweat loss.

Heat balance of the body (S; W/m^2) was calculated using a method of partitional calorimetry summarized in Equation 2 below.

$$S = M - W \pm (C \pm R \pm K) - E_{sk} - C_{res} - E_{res} \qquad \textbf{(2)}$$

The rate of metabolic heat production (M; W/m^2) was calculated from measured RQ and VO_2 (liters·min^{-1}) and the body surface area (A_D; m^2) as shown below in Equation 3.[20]

$$M = 352 \cdot (0.23 \cdot \mathrm{RQ} + 0.77) \cdot (\mathrm{VO_2}/\mathrm{A_D}) \qquad \textbf{(3)}$$

The rate of mechanical work (W; W/m^2) was calculated as shown in Equation 4 below,[21] where M_b is a clothed body mass (kg), V_w is the treadmill walking speed (m·min^{-1}), and F_g is a fractional grade of the treadmill.

$$W = 0.163 \cdot \mathrm{M_b} \cdot \mathrm{V_w} \cdot \left(\mathrm{F_g} \cdot \mathrm{A_D^{-1}}\right) \qquad \textbf{(4)}$$

The rate of dry heat exchange (W·m^{-2}) through convection (C), radiation (R), and conduction (K) was directly measured using the heat flow sensors attached to the eight skin sites. Prior to the onset of testing, a factory-determined calibration constant (W/m^2·mv^{-1}) for each heat flow sensor was input into a data acquisition system, and the weighted mean heat flux was calculated using the same T_{sk} coefficient previously described.[19]

The rate of evaporative heat loss (E; W/m^2), as shown below in Equation 5, was directly determined from changes in pre-post nude body weight with the weight gain in underwear, PPE, and other absorbent materials (e.g., HR chest strap) for non-evaporative sweat loss, where m_{sw} is the sweat loss (g·h^{-1}) by evaporation and λ is latent heat of sweat vaporization (0.68 W·h·g^{-1}). Weight loss due to E_{res} and O_2/CO_2 exchange was also corrected for the E_{sk} calculation.

$$E_{sk} = \mathrm{m_{sw}} \cdot \lambda \cdot \mathrm{A_D^{-1}} \qquad \textbf{(5)}$$

The rate of respiratory heat exchange (W/m^2), shown below in Equation 6, through convection (C_{res}) and evaporation (E_{res}) was calculated by the combined equation,[21] where T_a is an ambient temperature in °C and P_a is partial pressure of water vapor in the ambient air in kPa.

$$C_{res} + E_{res} = 0.0012 \cdot M \cdot (34 - \mathrm{T_a}) + 0.0173 \cdot M \cdot (5.87 - \mathrm{P_a}) \qquad \textbf{(6)}$$

Statistical Analysis

Data from SHP and STM were presented as average and standard deviation values, across three repeated tests, according to the standard test methods.[7,17,18] Data from human testing were summarized and presented as 1 min average and standard deviation across the subjects for statistical analysis. T_{re}, T_{sk}, HR, RH_{micro}, and T_{micro} were compared using two-way repeated measured ANOVA at 0 min and each 15 min to the end of the testing (Ensemble × Time) and all other non-time-related variables (sweat production, calorimetry data, clothing characteristics, and so on) were compared using paired sample t-tests within the same environmental condition. For a significant F-ratio detected by ANOVA analysis, post-hoc pairwise comparison accompanied with Bonferroni corrections were carried out. Statistical significance was accepted when $p < 0.05$. All analyses were carried out using a statistical software package (SPSS V.18, IBM, Somers, N.Y.).

RESULTS

SHP and STM Tests

The results for thermal characteristics of the study fabric and ensemble are summarized in Table I. The manufacturer tested THL value of the fabrics A and B; 200 W/m^2 and 900 W/m^2, respectively, were in agreement with our test results 191.3 W/m^2 and 909.3 W/m^2 respectively, with a standard deviation of less than 10% from three repeated tests. These THL values were significantly lower, 81.5 W/m^2 and 149.9 W/m^2, respectively, resulting from a significant increase in thermal and evaporative resistance when tested as whole ensemble on the STM.

Human Test

All ten subjects, whose data are presented here, completed four trials of the ensemble testing while two subjects from the initial subject pool were removed from the study due to their inability to complete the protocol in a hot/humid environment. In the trial of ensemble A + hot/humid condition, six of the subjects reached the exercise termination T_{re} approved by the NIOSH review board at 50–55min of exercise at which time exercise was terminated, but they remained clothed at the same environment until the completion of 60 min of data collection.

Thermo-physiological variables

There was a main effect of ensemble ($F = 32.78$ and 37.75, $p < 0.001$) and time ($F = 140.02$ and 416.93, $p < 0.001$) on T_{re} in both mild and hot/humid conditions, respectively. T_{re} gradually increased throughout 60 min of exercise in all trials, while the magnitude of T_{re} increase was significantly greater in ensemble ***A*** condition (Figure 1A). There was a main effect of ensemble ($F = 74.77$ and 120.92, $p < 0.001$) and time ($F = 41.41$ and 780.72, $p < 0.001$) on T_{sk} in both mild and hot/humid conditions, respectively. T_{sk} increased progressively throughout all trials, with a significantly greater increase in ensemble A condition from an early phase (10–15 min) of exercise (Figure 1B). There was a main effect of ensemble ($F = 53.66$ and 34.92, $p < 0.001$) and time ($F = 221.57$ and 390.20, $p < 0.001$) on HR in both mild and hot/humid conditions, respectively. Similarly, HR increased gradually until the cessation of exercise, with a significantly greater exertion of HR in ensemble A condition (Figure 1C).

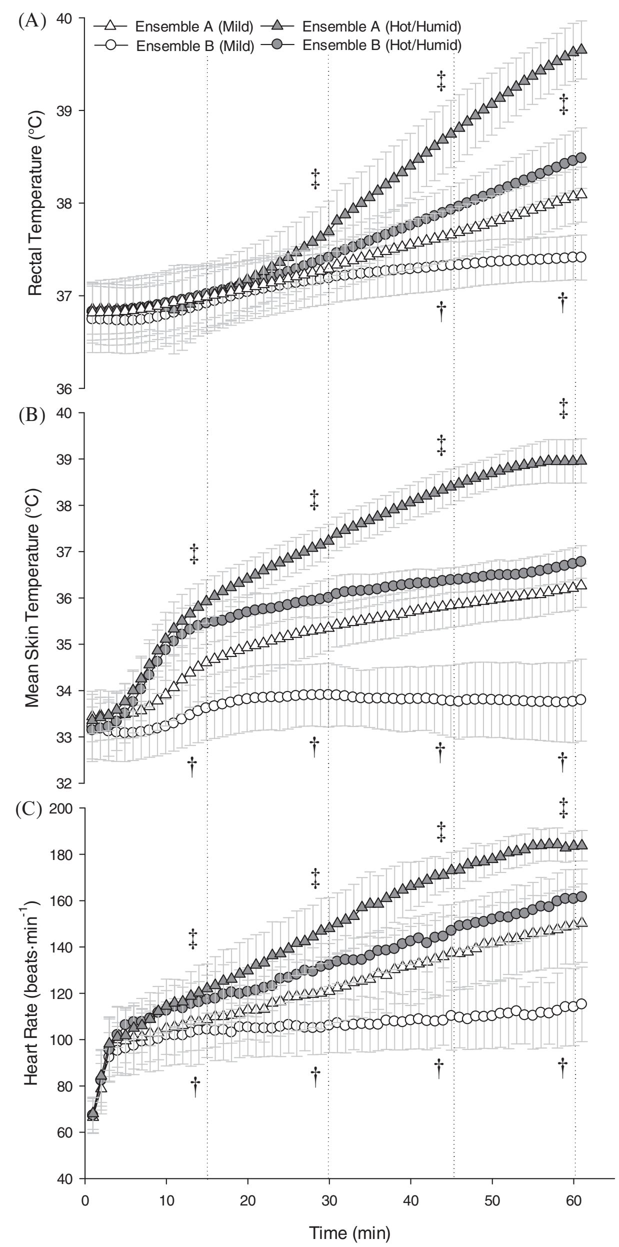

FIGURE 1. Rectal temperature (A), mean skin temperature (B), and heart rate (C) response during human testing (Values are mean and standard deviation (vertical bars). Symbols denote a statistical difference ($p < 0.01$) between ensemble A and B in mild (†) and hot/humid (‡) condition).

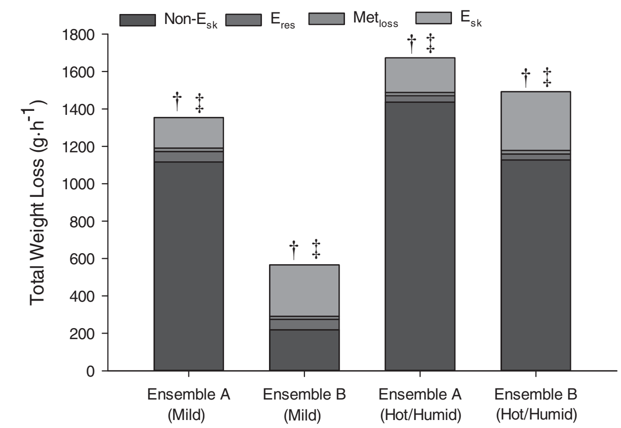

FIGURE 2. Total weight loss during human ensemble testing (stacked by each weight loss element) (Values are mean. Non-E_{sk}: non-evaporative sweat loss, E_{res}: evaporative loss through respiration, Met_{loss}: metabolic weight loss due to O_2/CO_2 exchange, and E_{sk}: evaporative sweat loss. Symbols denote a statistical difference ($p < 0.05$) between ensemble A and B in E_{sk} (†) and Non-E_{sk} (‡).)

Sweat production

Total sweat loss was significantly greater in ensemble *A* than ensemble *B* trial in both mild ($t = -6.97$, $p < 0.001$) and hot/humid ($t = -2.33$, $p < 0.05$) conditions. Further analysis of the total sweat loss by evaporative and non-evaporative sweat loss is shown in Figure 2. Despite a greater sweat production in ensemble *A*, evaporative sweat loss was significantly greater in ensemble *B* ($t = 3.02$, $p < 0.05$) and a therefore greater amount of non-evaporative sweat loss in ensemble *A* than in ensemble *B* ($t = -9.62$, $p < 0.001$) in the mild condition. Similarly, evaporative sweat loss was significantly greater in ensemble *B* than ensemble *A* ($t = 2.69$, $p < 0.05$), with a significantly greater amount of non-evaporative sweat loss in ensemble *A* than ensemble *B* in the hot/humid condition ($t = -3.65$, $p < 0.01$).

Calorimetry data

Each component of the partitional calorimetry data is summarized in Table II. The rate of metabolic heat production (M) did not differ between ensembles in the mild condition ($t = -0.70$, $p = 0.50$); however, it was significantly greater in ensemble *A* than *B* in hot/humid condition ($t = -2.74$, $p < 0.05$). There was a significant difference in dry heat loss ($R + C + K$) between ensembles in the mild ($t = 7.78$, $p < 0.001$) and hot/humid ($t = 4.92$, $p < 0.01$) conditions. The rate of evaporative heat loss from the skin (E_{sk}) differed significantly between ensembles in both mild ($t = 3.02$, $p < 0.05$) and hot/humid conditions ($t = 2.78$, $p < 0.05$), as shown in the sweat production result above. Lastly, there was no difference in the rate of mechanical work (W) and respiratory heat loss through convection and evaporation ($C_{res} + E_{res}$) between the ensembles in both environmental conditions ($p > 0.05$).

Microclimate temperature and humidity

There was a main effect of ensemble ($F = 124.13$ and 181.30, $p < 0.001$) and time ($F = 9.23$ and 429.90, $p < 0.001$) on T_{micro} in both mild and hot/humid conditions, respectively. T_{micro} was prematurely elevated above ambient temperature during the stabilization period (22°C) in all conditions due to the wearing of the full encapsulating ensembles. T_{micro} then progressively increased during exercise, reaching and/or increasing above the ambient temperature of the testing conditions, except in ensemble *B* mild condition in which T_{micro} remained slightly decreased and/or plateaued throughout the exercise (Figure 3A). There was also a main effect of

TABLE II. Summary of the Rate of the Body Heat Exchange in Human Testing

Condition						
Environment	Ensemble	M	W	$C+R+K$	E_{sk}	$C_{res}+E_{res}$
Mild	*A*	243.3 (26.3)	16.5 (0.8)	65.5 (11.2^{A}	55.0 (32.3)^{A}	21.8 (3.1)
	B	239.6 (21.7)	16.2 (0.8)	86.6 (6.9)^{A}	92.4 (26.7)^{A}	21.4 (2.4)
Hot/Humid	*A*	289.9 (32.8)^{B}	16.5 (0.8)	29.8 (2.6)^{B}	61.7 (25.2)^{B}	10.8 (1.2)
	B	272.5 (33.7)^{B}	16.2 (0.8)	41.8 (7.3)^{B}	105.2 (44.9)^{B}	10.1 (1.4)

Notes: Values are mean (SD) in W/m^2. M: the rate metabolic heat production, W: the rate of mechanical work, $C+R+K$: the rate of dry heat exchange through convection (C), radiation (R), and conduction (K), E_{sk}: the rate of evaporative heat loss from skin surface, and $C_{res}+E_{res}$: the rate of respiratory heat exchange through convection (C_{res}) and evaporation (E_{res}). The rate of body heat storage (S) could be calculated as $S = M - W - (C+R+K) - E_{sk} - (C_{res}+E_{res})$. Symbols denote a statistical difference (p < 0.05) between ensemble A and B in mild (^{A}) and hot (^{B}) condition.

ensemble ($F = 18.91$ and 25.27, $p < 0.01$) and time ($F = 111.76$ and 486.10, $p < 0.001$) on RH_{mico} in both mild and hot/humid conditions, respectively. Similarly, RH_{micro} increased above baseline ambient relative humidity (30%) in all trials and this initial increase was significantly greater in ensemble *A* than *B* in both mild and hot/humid conditions. Following the onset of exercise, there was an abrupt increase in RH_{micro} with a significant impact related to ensemble type and ambient condition (Figure 3B).

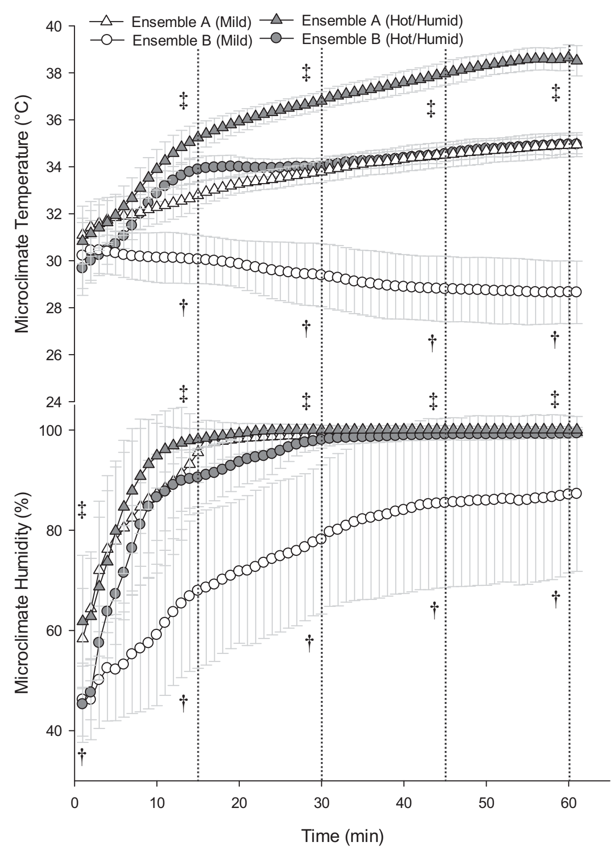

FIGURE 3. Microclimate temperature (A) and humidity (B) response during human testing (Values are mean and standard deviation (vertical bars). Symbols denote a statistical difference (p < 0.05) between ensemble A and B in mild (†) and hot/humid (‡) condition.)

DISCUSSION

The present results clearly demonstrate a considerable difference in thermal and evaporative resistance measurements between fabric and ensemble (Table I). This is perhaps not surprising but expected when considering innate distinctions in the testing configuration of the two methods[22]—along with added insulation and resistance from outer protective gloves, boots, resistive seams, and so on—which are not taken into account in the SHP test. Consequently, the calculated THL significantly differed between SHP and STM methods, showing that not only did THL decrease from a fabric level, but also the potential difference in THL between the two materials considerably diminishes (718.0 W/m^2 at SHP to 68.4 W/m^2 at STM). This offers a view that aan apparently large difference in fabric THL between two materials may not necessarily result in actual improvement in ensemble thermal characteristics and, further, such a decrease in THL is not uniformly proportional between ensembles when fabrics are constructed into a complete PPE ensemble. The specified environment for THL estimation in the STM test (20°C, 40% RH)[17,18] differs from that at SHP (25°C, 65% RH)[7], as the tests conditions are not identical between the methods. In our calculation, potential THL from the STM data adjusted for the SHP test environment showed further reduction in THL, but the difference was not notable compared to the standard STM test condition, showing 58.2 and 128.6 W/m^2 for ensembles *A* and *B*, respectively.

Despite the reduction in the difference of THL values between the SHP and STM tests, there was a significant difference in the subjects' physiological responses between the ensembles, evidenced by consistently higher T_{re}, T_{sk}, and HR in ensemble *A* (low THL) than in ensemble *B* (high THL) in both environmental conditions (Figure 1). The final T_{re}, as the main thermal stress index was (mean ± SD, ensembles *A* vs. *B*)

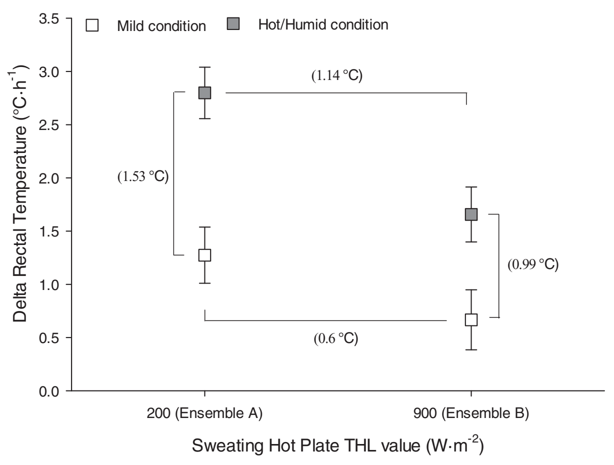

FIGURE 4. Changes in rectal temperature during human testing (Values are mean and standard deviation. Values in parentheses indicate mean difference in rectal temperature between trials.)

38.1 ± 0.3 vs. 37.4 ± 0.2°C in mild, and 39.7 ± 0.3 vs. 38.5 ± 0.3°C in the hot/humid condition, which could be interpreted as a fabric THL difference of 700 W/m^2 discriminate T_{re} of 0.6 and 1.14°C·h^{-1} between the two ensemble trials (Figure 4). This large difference, when other factors are constant (e.g., PPE design, work rate, environmental conditions), was mainly attributed to ensemble thermal properties influencing the body heat exchange in both dry and evaporative heat loss (Table II). As a specific interest of this study, it is shown that (by a fraction of the observed T_{re} elevation by the SHP-based THL difference with a linear relationship assumed) T_{re} would increase by 0.09°C·h^{-1} (SD, 95% CI: 0.04, 0.06–0.12) and 0.16°C·h^{-1} (0.02, 0.15–0.18) in the mild and hot/humid condition, respectively, with every 100 W·m^2 of THL added under the current exercise condition.

Some data are available from previous studies investigating the relationship between a THL value and its effect on firefighter physiology.[23,24] Barker and colleagues,[23] who compared six firefighter ensembles with a THL range between 97 and 251 W/m^2 during intermittent treadmill exercise in mild (21°C, 65%RH) and hot (39°C, 35%RH) environments, found no significant difference in end-point T_{re} ($\Delta T_{re} \leq 0.2$°C) between ensembles with various THL. Stull and Duffy,[24] who compared seven firefighter ensembles with a THL range between 97 and 439 W/m^2 during a simulated extrication and ladder activities, also reported no significant or variable end-point T_{re} (ΔT_{re} 0.18–0.46°C·h^{-1}) between ensembles with a THL difference less than 100–150 W/m^2, but found a significantly suppressed T_{re} elevation when the two extreme ranges of THL (97 vs. 439 W/m^2) were compared. Collectively, the relationship between THL and physiological benefit in terms of body heat loss and thus core body temperature during work appears to be hyperbolic, as previously suggested.[24] While identifying a breakpoint or threshold for increased physiological benefit over the wide hyperbolic range of THL values would provide a clearer view, the present results, combined with others,[23,24] suggest PPE ensembles with a THL difference of less than approximately 150–200 W/m^2 would unlikely discriminate a level of thermal stress and/or suppress T_{re} elevation to meaningful degrees.

During physical performance in the heat, E_{sk} is a predominant pathway for heat release to the environment. Wearing a PPE ensemble encapsulating the body causes evaporative restriction that converts heat stress to an uncompensable state.[25,26] While our method to determine E_{sk} based on the changes in body weight may not be the most adequate for PPE ensemble conditions,[4,27] the present results of evaporative and non-evaporative profiles in sweat loss highlight a thermoregulatory challenge associated with wearing PPE ensembles (Figure 2). Sweat loss through E_{sk} was significantly higher in ensemble *B* than *A* in both mild and hot/humid conditions due to apparently lesser evaporative resistance with ensemble *B*. However, the total amount of sweat accounted for in E_{sk}, relative to non-evaporative sweat loss, was considerably less, even with increased thermoregulatory sweat production in the more breathable ensemble *B* in hot/humid condition, resulting in a higher rate of heat storage. T_{re} elevation (shown in ΔT_{re}, Figure 5) was therefore more influenced by environmental conditions than ensemble thermal properties. This is due to a significant reduction in the evaporative potential of the environment as a function of the increased partial pressure of water vapor in the ambient air (from 1.32 to 3.65 kPa in mild and hot/humid condition, respectively). This result supports the findings of the previous study[4] that demonstrated the impact of the ambient vapor pressure on heat strain in PPE ensembles, and also suggests that the sole improvement in PPE ensemble thermal properties may not necessarily induce considerable alleviation of heat stress in wearers, especially in hot/humid environments. Rather, as documented previously,[6,28] further improvement in clothing porosity, and thus increased ventilation that potentially results in elevated emission of microclimate heat and humid for better sweat evaporation and convective heat exchange, seems more promising to promote heat dissipation in users wearing a PPE ensemble.

The present study had two main limitations. First, the study evaluated only two representatives of protective fabrics with THL at the extremes of the NFPA standards. This was due to the limited availability of various protective fabrics and the cost of each testing procedure, including the construction of PPE ensembles. Second, the study did not consider other factors of protective fabric performance associated with hazard protection, which may greatly affect THL characteristics. For example, protective features such as flame/thermal barrier characteristics in firefighter PPE or chemical permeation factors in CBRN likely alter THL in various degrees because of added layers, reflective materials, and/or vapor resistance characteristics. Future studies should investigate relationships between protective performance and thermal characteristics of protective fabrics to aid optimal design and selection of PPE ensembles for a specific field of PPE utilization.

CONCLUSION

The present study was not intended to criticize the SHP test method or THL rating practice dealing with fabric composites. In fact, the SHP test is a valuable tool, validated as reproducible and repeatable in determining the thermal characteristics of fabrics,(9,10) which would help PPE manufacturers and researchers in textile sciences advance the thermal and protective performance of fabrics. On the other hand, applying THL values determined under static two-dimensional heat exchange conditions (SHP test) to prediction and/or interpretation of heat stress in a clothed human working in a dynamic three-dimensional thermal environment is seemingly problematic.

While NFPA standards(11–15) guide PPE thermal performance requirements based on the SHP test, we demonstrated that: (1) SHP-based THL measurements significantly differ from the actual THL potential of the PPE ensemble when tested using a STM method, which better model the thermal stress in humans; (2) physiological benefit in terms of alleviating a thermal stress (shown in core body temperature; T_{re} in the present study) acquired from wearing a more breathable PPE ensemble based on THL values may not be feasible with incremental THL values less than approximately 150–200 W·m^2, which appear to be hyperbolically related to total heat loss; and (3) thermal environments to which PPE ensemble wearers are exposed, have a greater impact on determining a level of heat stress on a wearer than ensemble thermal characteristics, due to the decreased evaporative potential of the environment limiting E_{sk} and inducing more humidity and heat in the ensemble microclimate. Therefore, design and engineering advances in PPE ensemble porosity and ventilation characteristics could help reduce heat stress associated with wearing PPE ensembles.

DISCLAIMER

The findings and conclusions in this article are those of the authors and do not necessarily represent the views of the National Institute for Occupational Safety and Health. Mention of product names does not imply endorsement. The authors identify no conflicts of interest in the conduct of this study. This article is not subject to US copyright law.

ACKNOWLEDGMENT

The authors are sincerely grateful for technical and experimental support from W.L. Gore & Associates Inc., Lion Apparel Inc., Underwriters Laboratories, and the Fabric Protection and Comfort Center at North Carolina State University. The subjects who generously volunteered their time to participate in this study are much appreciated.

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