Maximum Sustainable Work Rate for Five Protective Clothing Ensembles with Respect to Moisture Vapor Transmission Rate and Air Permeability

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The fabrics associated with protective clothing affect heat stress, which influences productivity and risks of heat-related disorders. This study compared the work limiting effects of five protective coveralls and a semiclothed condition (t-shirt and shorts). Two fabric characteristics determined from bench tests, moisture vapor transmission rate (MVTR), and air permeability were also examined as possible predictors of ensemble performance. A progressive metabolic rate protocol was used where environmental conditions ($T_{db} = 32°C$; $T_{pwb} = 26°C$) were held constant while treadmill speed was slowly increased. The limiting metabolic rate to just maintain thermal equilibrium was the critical point. At this point, critical speed and critical metabolic rate were noted and total evaporative resistance was calculated for each ensemble. Five acclimatized subjects wore each of the six clothing conditions in a random order. Statistically significant differences were found among the five protective garments and a semiclothed ensemble for critical treadmill speed (S_{crit}), critical metabolic rate (M_{crit}), and total evaporative resistance (R_{e-t}). The semiclothed condition ($S_{crit} = 1.77$ m/sec; $M_{crit} = 580$ W; $R_{e-t} = 0.0099$ kPa m²/W) and ensembles made from spunbonded, melt blown, spunbonded polypropylene (SMS) (1.72 m/sec; 560 W; 0.0135 kPa m²/W) and spunbonded polypropylene (1.67 m/sec; 550 W; 0.0126 kPa m²/W) were able to support higher work rates than fabrics made from Tyvek 1422-A (a nonwoven spunbonded olefin) (1.48 m/sec; 470 W; 0.0183 kPa m²/W) and a microporous film supported by spunbonded polypropylene (1.34 m/sec; 420 W; 0.0231 kPa m²/W). A tightly woven polyester ensemble (1.59 m/sec; 510 W; 0.0130 kPa m²/W) had intermediate values and was not significantly different from either group. Air permeability was a better predictor of fabric work limiting performance than MVTR. An air permeability on the order of 10,000 L/min cm² bar would have little effect on maximum sustainable work.

Keywords   heat stress, MVTR, permeability, protective clothing

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The management of heat stress is a challenge faced by many health and safety professionals. Frequently, workers may be exposed to a variety of chemical and biological agents. When engineering and administrative controls are inadequate to protect workers, the use of personal protective clothing can further complicate heat stress management.

An examination of the thermal balance model is helpful in understanding how clothing contributes to heat stress. Equation 1 is an expression of the heat balance equation.[1,2]

$$E_{req} = M_{net} + R + C + C_{res} - E_{res} - S \qquad (1)$$

The rate of evaporative cooling needed to maintain thermal equilibrium is frequently called required evaporative cooling (E_{req}). The body is in thermal equilibrium when there is no heat storage (S = 0). Net metabolic rate (M_{net}) is the rate of transformation of chemical energy into available energy to support physiological functions less the external work rate. The rate of radiant heat exchange (R) is the net rate of heat transferred from warmer to cooler surfaces by infrared radiation. Convective heat exchange (C) is the rate of transfer of heat between the air and the surface of the skin due to air motion. Both R and C are affected by clothing through insulation qualities. Some heat exchange also occurs in the respiratory tract as conduction (C_{res}) between the air and tissues, and as evaporative cooling (E_{res}) with the evaporation of water in the respiratory track. If maximum evaporative cooling (E_{max}) cannot meet the required evaporation (E_{req}) the body will store heat and core body temperature will rise (S > 0). The maximum evaporative cooling depends on differences in vapor pressure between the skin and the air, clothing permeability, and air velocity. E_{max} may also have a physiological limit, which is usually not the limit when protective clothing is worn.

One way to assess the effects of protective clothing is through the determination of thermal characteristics of clothing, and another is by measuring the sustainable level

of work that can be achieved while wearing the protective clothing.

Thermal Characteristics of Clothing

It is clear that clothing affects heat exchange through insulation and permeability characteristics.[3] Total insulation (I_t) is a measure of how clothing and the surrounding boundary layer of air modifies the rate of dry heat exchange (radiant and convective). Total evaporative resistance (R_{e-t}) is a measure of water vapor mobility through the clothing and includes the effect of the boundary layer of air. As total evaporative resistance increases, the maximum rate of evaporative cooling decreases. These thermal properties have been studied using bench tests (e.g., hot plate methods), heated copper mannequins, and wear tests.

Moisture vapor transport rate (MVTR) is a bench test measure of the rate of water vapor movement through a fabric and is expressed as the amount of water that moves across a fabric sample per unit area per unit of time (e.g., g/m^2 day). An American Society for Testing Materials (ASTM) standard for MVTR[4] controls the vapor pressure gradient across the fabric sample. It is commonly believed that MVTR adequately measures the evaporative cooling capacity of a fabric. The higher the MVTR, the more evaporative cooling a fabric can allow. However, MVTR is a measure of vapor transport by molecular diffusion. Woodbridge[5] found that simple diffusion could not explain supported heat exchange at high work rates. Kawabata et al.[6] proposed the sweating hot plate to better simulate heat exchange from the skin compared to the dry hot plate and MVTR methods. Sweating hot plate methods are useful for selecting fabrics for use in protective garments but the heat transfer coefficients cannot be directly compared unless test conditions are identical.

Kenney et al.[1] used human participants to evaluate the thermal characteristics of protective clothing. Tests were conducted in a climatic chamber where environmental conditions could be manipulated. Barker et al.[2] followed a similar approach. In both protocols, metabolic rate was constant and the participant's core temperature (T_{re}) and average skin temperature (T_{sk}) were monitored. When thermal equilibrium could no longer be maintained, T_{re} rose sharply. The point just prior to the core temperature rise was noted and referred to as the inflection point. This allowed the critical temperature (T_{crit}) and the critical water vapor pressure (P_{crit}) to be identified. At these critical points, the required rate of evaporative cooling (E_{req}) was equal to the maximum rate of evaporative cooling (E_{max}).

The maximum rate of evaporative cooling (E_{max}) was defined as the difference between the skin water vapor pressure (P_{sk}) and the ambient water vapor pressure divided by the total evaporative resistance (R_{e-t}).

$$E_{max} = (P_{sk} - P_a)/R_{e-t} \qquad (2)$$

(R + C) is the dry heat exchange. Without a specific radiant heat source, the difference in T_{db} and T_{sk} divided by the total clothing insulation (I_t) is an estimate of dry heat exchange.

That is,

$$(R + C) = (T_{db} - T_{sk})/I_t \qquad (3)$$

Equations 2 and 3 were substituted into Eq. 1 to form Eq. 4.

$$(P_{sk} - P_a)/R_{e-t} = M_{net} + (T_{db} - T_{sk})/I_t + C_{res} + E_{res} - S \qquad (4)$$

When I_t is estimated, then R_{e-t} can be calculated from single experiments. Following this approach, Barker et al.[2] reported wear tests of protective garments in a climatic chamber. They found significant differences in evaporative resistance (R_{e-t}) among a variety of existing and prototype limited-use fabrics.

Maximum Sustainable Metabolic Rate and Fabric Characteristics

Bernard and Matheen[7] developed the maximum sustainable metabolic rate (maximum sustainable work rate) protocol to examine the effects of two different protective clothing ensembles on productivity in a fixed environment. The protocol was designed to ask how much work can be sustained for prolonged periods of time (nominally 2 hours without a break). This protocol was also used by Barker et al.[8] to look for productivity and evaporative resistance differences among five limited-use coveralls with hood.

It is interesting to compare fabric performance in the sustained work protocol to bench tests of fabrics. Table I is a summary of fabric types, bench test results and experimental results from Barker et al.[8] following the protocol of Bernard and Matheen.[7] Figure 1 presents mean critical treadmill speeds with whiskers showing the standard error of the mean plotted against moisture vapor transmission rates (MVTR) for each fabric. MVTR values did not appear to relate well to sustainable work as reflected in critical treadmill speed when the means were related through a least squares linear regression
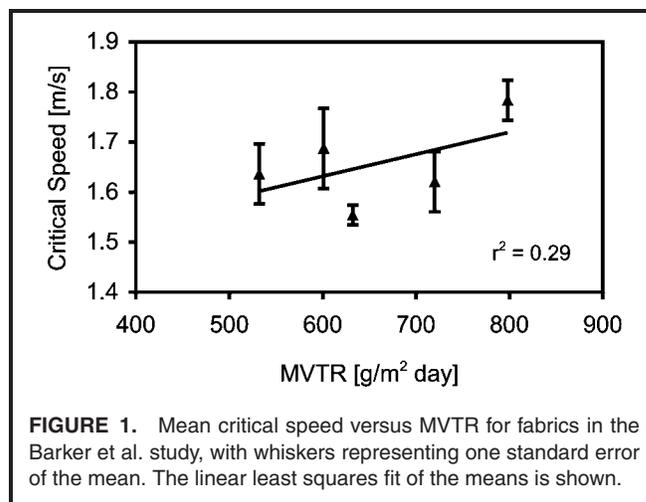

FIGURE 1. Mean critical speed versus MVTR for fabrics in the Barker et al. study, with whiskers representing one standard error of the mean. The linear least squares fit of the means is shown.

TABLE I.   Fabrics for Limited-Use Coveralls with Hood

Ensemble and Fabric Description	MVTR (g/m² day)	Air Permeability (L/min) (cm² bar)	R$_{e-t}$ (kPa m²/W)	Critical Speed (m/sec)	Metabolic Rate (watts)
SMS (Kimberly-Clark Kleenguard GP Coverall)	800	940	0.0086 ± 0.0003	1.78 ± 0.04	530 ± 20
Trial fabric film (noncommercial microporous film from a process of phase separation)	720	0.35	0.0111 ± 0.0006	1.62 ± 0.08	460 ± 40
Trial fabric treated (Tyvek 1422-A topically treated to render it wettable/wickable)	600	3.7	0.0112 ± 0.0013	1.69 ± 0.06	490 ± 30
Tyvek 1422-A (DuPont commercial spunbonded polyolefin)	530	3.1	0.0156 ± 0.0016	1.64 ± 0.06	480 ± 30
SFS (DuPont Proshield 2)	630	0.13	0.0160 ± 0.0017	1.55 ± 0.02	450 ± 20

Notes: Experimental results from Barker et al.;[2,8] MVTR = moisture vapor transmission rate; R$_{e-t}$ = total evaporative resistance. Clothing characteristics and results in mean $\pm$ standard error of the mean.

($r^2 = 0.29$). The two fabrics that deviated the most from the regression line were those with a vapor-transmitting film. Whereas the film has good moisture transfer characteristics based on MVTR, it did not support sustained work as well as other fabrics.

To help explain the differences among fabrics, air permeability was examined. Air permeability is the ability of the fabric to support airflow through the fabric (convection) under small pressure gradients. (See Methods for a description of the method used to measure air permeability.) When the critical treadmill speed data were plotted against air permeability on a semilogarithmic scale, a stronger relationship appeared (see Figure 2). With $r^2 = 0.93$, there was a clear improvement in the relationship to mean critical treadmill speed.

To explore the role of air permeability on sustainable work, five different fabrics were selected for this study for which the

FIGURE 2.   Mean critical speed versus air permeability for fabrics in the Barker et al. study with whiskers representing one standard error of the mean. The line represents a logarithmic least squares fit of the means.

rates of air permeability were distributed over four orders of magnitude. In addition, a semiclothed (SC) condition was a marker for the upper limit on air permeability associated with no clothing limits on sustainable work.

METHODS

Air Permeability

A Coulter Porometer II capillary porometer (Coulter Electronics, Miami, Fla.) was used to measure air permeability. Airflow rates were measured on 25 mm diameter circular fabric samples at pressure drops ranging from 0.02 to 5 bar, as set by the user depending on fabric permeability. The instrument output of air flow in liters per minute per square centimeter was normalized to a pressure drop of 1 bar to obtain the Coulter Permeability, L/min cm² bar.

Clothing Characteristics

Clothing characteristics for the current study are listed in Table II and include fabric weight and thickness, moisture vapor transmission rate, and air permeability.

During the experiments, participants wore a cotton t-shirt and shorts under coveralls made from the different fabrics. Ankles and wrist cuffs were snugly taped. Hoods were adjusted for comfort and then secured with tape at the neck. Because the polyester coveralls did not have an integral hood, a similar polyester hood from a nuclear anticontamination ensemble was used, with the bib of the hood placed under the coverall and taped to the collar. Participants also wore shoes and socks.

Participants

Five male participants were used in this experiment. See Table III for their physical characteristics. All were paid volunteers and Institutional Review Board practices for written informed consent were followed.
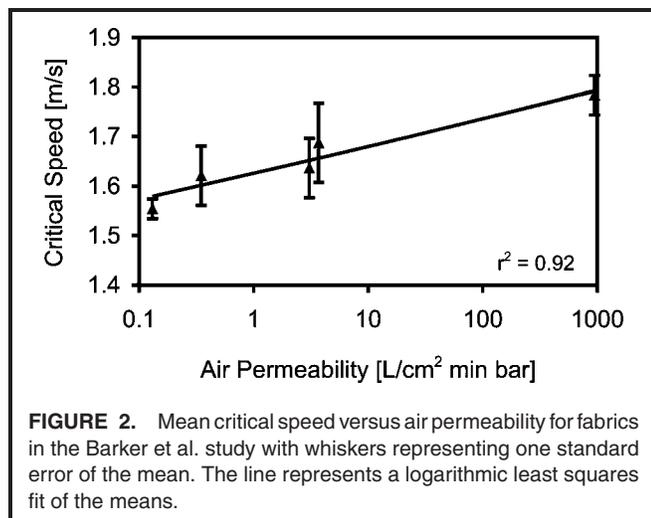
TABLE II. Clothing Characteristics and Results for Present Study

Ensemble and Fabric Description	Weight (g/m²)	Thickness (mm)	MVTR (g/m² day)	Air Permeability (L/min cm² bar)	R_{e-t} (kPa m²/W)	Critical Speed (m/sec)	Metabolic Rate (watts)
SC (semiclothed)	—	—	—	—	0.0099 ± 0.0008	1.77 ± 0.09	580 ± 40
SMS (Kimberly-Clark Kleenguard GP Coverall)	44	0.24	900	830	0.0135 ± 0.0009	1.72 ± 0.07	560 ± 30
SBPP (Spunbonded Polypropylene Coverall from Lakeland Industries, Inc.)	44	0.26	1600	1600	0.0126 ± 0.0009	1.67 ± 0.03	550 ± 30
Tight woven polyester clean room coverall (Superior Uniform Worklon)	96	0.13	880	46	0.0130 ± 0.0008	1.59 ± 0.09	510 ± 40
Tyvek 1422-A (DuPont Commercial Spunbonded Polyolefin)	43	0.13	560	5.9	0.0183 ± 0.0017	1.48 ± 0.03	470 ± 30
SFS (Kimberly-Clark Kleenguard Ultra Coverall)	62	0.21	690	0.30	0.0231 ± 0.0025	1.34 ± 0.05	420 ± 30

Note: Clothing characteristics and results in mean ± standard error of the mean.

Equipment

The experiments were conducted in a climatic chamber. Air movement was nominal at 0.5 m/sec. A treadmill was used to control participants' work rates.

Heart rates were continually monitored with a three-lead electrocardiograph system. Skin temperatures were continually monitored with surface thermistors taped to the chest, thigh, calf, and upper arm. Average skin temperature was computed as $T_{sk} = 0.3\ T_{ch} + 0.3\ T_{arm} + 0.2\ T_{th} + 0.2\ T_{calf}$.[9] Core temperature ($T_{re}$) was measured with a flexible thermistor inserted 10 cm beyond the anal sphincter muscle.

Oxygen consumption was used to estimate metabolic rate. Participants placed a clip on their nose and then breathed through a mouthpiece attached to a two-way valve. Expired air was collected via a flexible hose to a Douglas bag for 2 or 3 min. A dry gas meter was used to measure the volume of expired air. A small sample was taken from the Douglas bag and drawn through a drying agent into an oxygen analyzer to measure oxygen content. Oxygen consumption was then calculated and converted to standard temperature and pressure dry (STPD) to assess the metabolic rate (M).[10]

Protocol

Prior to the start of the trials all participants were acclimatized for 5 consecutive days, with 2-hour exercise sessions each day in the chamber. During these sessions, a dry bulb temperature (T_{db}) of 50°C at 20% relative humidity was maintained. Participants walked at a rate of 1.56 m/sec (3.5 mph) with 0% grade wearing shorts, shoes and socks.

The actual experimental trials followed a progressive metabolic rate protocol that was designed to increase heat stress by increasing the metabolic rate (M). Dry bulb temperature (T_{db}) was set at 32°C and psychometric wet bulb temperature (T_{pwb}) was set at 26°C. Participants started each trial at a treadmill speed of 1.56 m/sec (3.5 mph). After 30 minutes, speed was reduced and maintained at 1.34 m/sec (3.0 mph) until thermal equilibrium was established. After equilibrium was achieved, treadmill speed was increased 0.045 m/sec (0.1 mph) every 5 min. Treadmill grade was constant throughout the study. Four of the five participants walked at a 2.5% grade. One participant walked at a 5.0% grade to obtain an adequate increase in metabolic rate with increases in treadmill speed.

During each trial, participants were permitted to drink either water or a commercial fluid replacement drink as desired. Data were monitored continuously and recorded at 5-min intervals. Expired air was collected at 30, 60, and 90 min into each trial. Trials were stopped if a participant's core temperature (T_{re}) increased at least 0.1°C for three consecutive 5-min intervals, if the participant reached a T_{re} of 39°C, if the participant

TABLE III. Participant Characteristics

Participant	Age (years)	Height (cm)	Weight (kg)	Body Surface Area (m²)
G1	23	180	77	1.96
G2	22	191	98	2.27
G3	23	183	86	2.08
G4	23	187	88	2.14
G5	26	178	76	1.93
Mean ± standard deviation	23 ± 2	184 ± 5	85 ± 9	2.08 ± 0.14

had a sustained heart rate greater than 90% of age-estimated maximum heart rate (estimated $HR_{max} = 195–0.67$ [Age –25]), or if the participant wished to stop.

Each participant completed this protocol in each of the five ensembles as well as semiclothed condition. The six trials were randomly assigned to each of the five participants. From past experience, five participants is enough to distinguish important differences.

Statistical Analysis

Statistical analyses were performed using JMP statistics software (version 3, SAS Institute, Cary, NC). Tukey's Honestly Significant Difference (HSD) was calculated if differences among protective garments was found to be significant at the $\alpha = 0.05$ significance level.[11] Least squares regressions were performed on mean values of the dependent variables (critical treadmill speed and metabolic rate) as related to the independent measures of MVTR, air permeability, and total evaporative resistance.

RESULTS

Inflection points were determined visually by noting the time at which T_{re} began to increase steadily and then noting the conditions in the prior five minute interval. Following Barker et al.[2] total insulation (I_t) was taken to be 0.086°C m^2 W^{-1} for the coveralls and 0.060°C m^2 W^{-1} for semiclothed. Total evaporative resistance (R_{e-t}) values for each of the garments were calculated using Eq. 4. Table II summarizes the results.

The maximum sustainable work rate is reflected in treadmill speed at the inflection point. Average critical treadmill speed among the ensembles were significantly different (p = 0.0001). Tukey's HSD at $\alpha = 0.05$ was 0.21 m/sec^{-1}. The SFS and Tyvek 1422-A were not different and associated with the lowest critical speeds and the SBPP, SMS, and semiclothed configurations were not different with the highest critical speeds. The polyester coveralls had an intermediate critical speed and was not different from any of the other clothing treatments.

Metabolic rate was driven by the work demands for walking on the treadmill. Metabolic rates were significantly different (p = 0.0001). Tukey's HSD for the mean metabolic rate was 80 watts. As with critical speed, semiclothed, SMS and SBPP were not different with the highest metabolic rates and SFS and Tyvek 1422-A were not different with the lowest metabolic rates; polyester coveralls were not different from any of the others with an intermediate value for metabolic rate.

The maximum sustainable work should be inversely proportional to total evaporative resistance. Differences among evaporative resistances were significant (p = 0.0001). Among the evaporative resistances, HSD was 0.0057 kPa m^2 W^{-1}. The relative groupings and order of clothing conditions follow that found for critical speed and metabolic rate with less differentiation among ensembles. One grouping within the

HSD range was the lower total evaporative resistance values of semiclothed, SBPP, SMS, and polyester coveralls; a second grouping with intermediate total evaporative resistance values was the SBPP, SMS, polyester coveralls, and Tyvek 1422-A; the third grouping of the higher total evaporative resistances was Tyvek 1422-A and SFS.

A fabric's total ability to allow evaporative cooling should affect sustainable work (i.e., critical speed and metabolic rate) and total evaporative resistance. MVTR is the conventional bench measurement used to describe the fabric's allowance for water vapor transport in support of evaporative cooling. The coefficients of determination (r^2) for the means of critical speed, metabolic rate, and total evaporative resistance versus MVTR were 0.39, 0.42, and 0.41. In each case, the SFS and the SMS results deviated clearly from the regression line and the SBPP MVTR appeared to be unusually high. Accurate measurement of MTVR for SBPP is likely to be problematic given a high air permeability that permits convective effects to increase mass transfer. When the SBPP result was removed from the dataset, the coefficients of determination improved to 0.55, 0.54, and 0.54. The relationship for speed to MVTR for all of the data is shown in Figure 3.

Convective effects, which can enhance breatheability, and hence evaporative heat transfer, are related to fabric air permeability. In a similar manner, air permeability was compared to sustainable work and total evaporative resistance. Figure 4 illustrates critical speed versus air permeability on a semilogarithmic scale for the five coveralls. The critical speed increased as air permeability increased. The horizontal line represents the semiclothed condition, which should be a practical limit. The r^2 was 0.96.

When metabolic rate associated with the maximum sustainable work was considered, the same relationship was evident for fabric air permeability. The r^2 was 0.97. For the relationship between air permeability and total evaporative resistance values (R_{e-t}), the r^2 was 0.86.
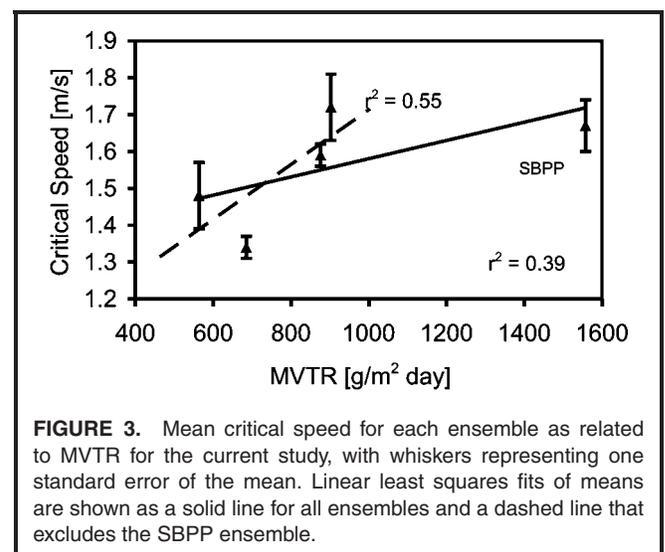

FIGURE 3. Mean critical speed for each ensemble as related to MVTR for the current study, with whiskers representing one standard error of the mean. Linear least squares fits of means are shown as a solid line for all ensembles and a dashed line that excludes the SBPP ensemble.

FIGURE 4. Mean critical speed for each ensemble versus air permeability for the current study, where the line represents the semiclothed case. The whiskers representing one standard error of the mean. The line represents a logarithmic least squares fit.
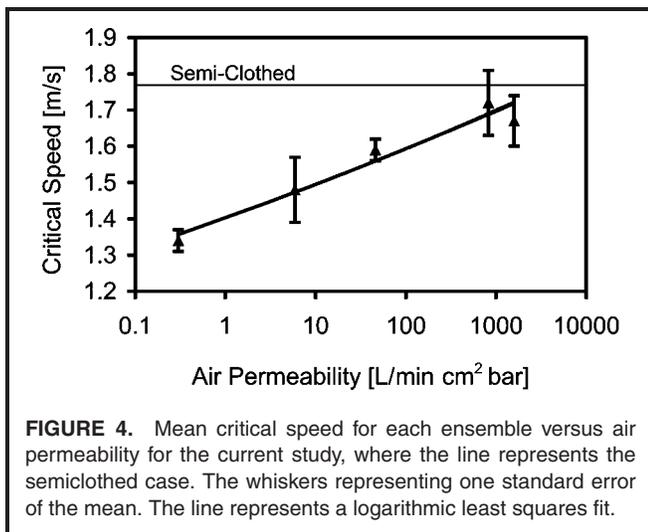
DISCUSSION

For this study, total evaporative resistance (R_{e-t}) for the five coveralls was calculated from Eq. 4 using the estimated I_t value of 0.086°C m²/W from Barker et al.[2] If the value of I_t changed by ±25% the calculated evaporative resistance (R_{e-t}) changed by only 10%.[2] The robust nature of the R_{e-t} estimate was also reported by Bernard and Matheen.[7]

From a two-way ANOVA (participants and ensembles), significant differences were found among the ensembles for critical speed, metabolic rate, and total evaporative resistance (R_{e-t}) as shown in Table II. For both measures of maximum sustainable work (i.e., critical speed and metabolic rate) as well as total evaporative resistance, there were significant differences among the clothing conditions and the rank ordering was consistent for the three measures. Confirming the results of Barker et al.[8] a strong relationship was not observed when moisture vapor transmission rates were compared to average critical treadmill speeds for each garment (see Figure 3). Likewise, MVTR did not predict average sustainable metabolic rate or total evaporative resistance for the ensembles in this study.
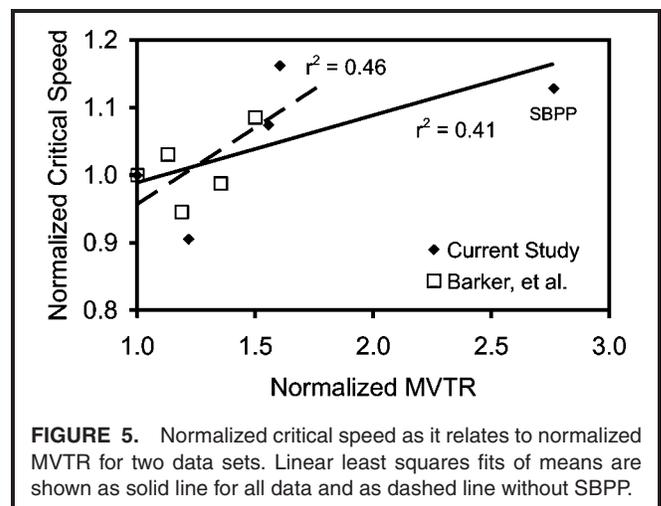
Looking for a better explanation, air permeability was compared to the degree of maximum sustainable work and total evaporative resistance. The air permeability of the fabrics studied in the current study covers the broad spectrum from the low permeability of microporous films to the very high permeability of a spunbond fabric. This broad spectrum of air permeability makes it difficult to use a single measurement technique to characterize both the low and high permeability fabrics. Typically, the Frazier permeability test (ASTM D737-96) used for woven fabrics is suitable for highly permeable fabrics. Frazier units of airflow are cubic feet per minute per square foot. The measurements are made at a pressure drop of 0.5 inches of water column. For low permeability fabrics, the Gurley or Gurley-Hill method (ISO 5636-5) can be used. This test measures the seconds (ranging between 5 and 1800 sec)

required for 100 mL of air to pass through 1 square inch of a sample at a pressure drop of 125 mm of water column. For the current study, a third option, the Coulter Porometer II capillary porometer was used to measure both low and high air permeability.

Air permeability rates were better correlated with ensemble performance than MVTR. Higher air permeability rates were associated with higher critical speeds (see Figure 4) and metabolic rates. An improved relationship between air permeability and R_{e-t} was also found.

The semiclothed condition was added to the experimental design to represent the baseline clothing that was worn with all ensembles. In this way, it would represent the least resistance to evaporative cooling and the highest values of air permeability and MVTR. Therefore, it should be the practical limit to the effect of protective clothing over the baseline clothing. From Figure 4, the extension of the least squares fit toward the semi-clothed value occurred at an air permeability on the order of 10,000 L/min cm² bar. The same was observed for metabolic rate and total evaporative resistance. In other words, a fabric designed to have air permeability greater than this would not likely increase the maximum rate of sustainable work.

Because there were different participant pools, treadmill slopes, and fabric samples between the current study and the Barker study,[8] it is difficult to directly compare the results. An approach to resolving these differences was to normalize the data to Tyvek 1422-A conditions, since this was one of two common fabrics in both data sets and had independent and dependent variable values more in the mid-range than the other common fabric (SMS). This was done by dividing the average speeds, metabolic rates and total evaporative resistances by the values for Tyvek 1422-A in each study. Likewise, the MVTR and air permeability values in each data set were divided by that for Tyvek 1422-A. The results for MVTR versus speed are shown in Figure 5. Again, the data for fabrics with microporous films fall off the trend for all the fabrics.
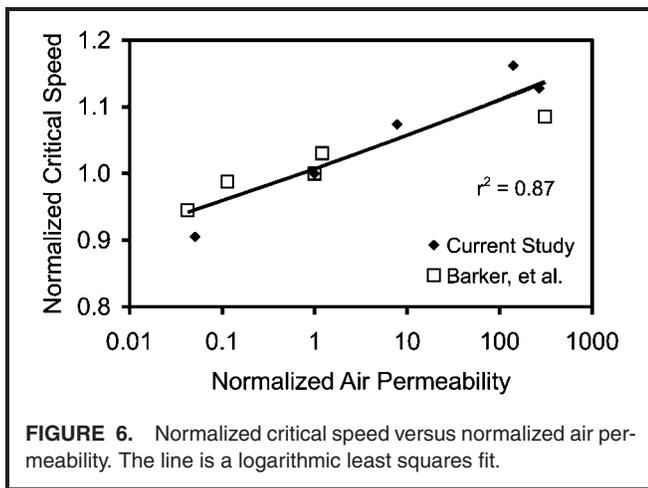

FIGURE 5. Normalized critical speed as it relates to normalized MVTR for two data sets. Linear least squares fits of means are shown as solid line for all data and as dashed line without SBPP.

FIGURE 6. Normalized critical speed versus normalized air permeability. The line is a logarithmic least squares fit.

Normalized air permeability versus normalized values for speed, metabolic rate and R_{e-t} for the current study and the Barker data set was explored. For all cases, a clear correlation was seen between air permeability and critical speed, metabolic rate and R_{e-t}. In each case, the correlation with air permeability of the garment was much stronger than the correlation with MVTR.

Figure 6 illustrates the normalized critical speed from both studies versus the normalized air permeability. The normalized critical speed increased as normalized air permeability and normalized MVTR increased. The r^2 was 0.87 for air permeability versus 0.46 for MVTR. This illustrates a stronger relationship between air permeability and maximum sustainable work.

In a similar manner, normalized critical metabolic rate was compared to normalized air permeability and normalized MVTR. As expected, normalized metabolic rate increased as normalized air permeability and normalized MVTR increased. The r^2 was 0.92 for air permeability versus 0.45 for MVTR. When normalized evaporative resistances (R_{e-t}) were compared to normalized air permeability and normalized MVTR, the r^2 was 0.52 for air permeability versus 0.23 for MVTR.

Woodbridge[5] recognized that simple diffusion, which is measured by MVTR, cannot explain heat loss by sweat evaporation. Overall, air permeability is the fabric property which better predicted the work limit achievable in a protective garment. This enhanced evaporative cooling can be supported by the motions of active work that can create small ventilating air flows across the fabric. Such convective flows would overshadow moisture transport by diffusion.

CONCLUSIONS

The purpose of this study was to compare the work limiting effects of five limited-use anticontamination coveralls.

When examined by ANOVAs, there were differences among the ensembles for critical treadmill speed, critical metabolic rate, and total evaporative resistance (R_{e-t}).

Among the five ensembles, productivity (as measured by critical treadmill speed and critical metabolic rate) was the least for the ensembles with lower air permeability made of a laminated microporous film and conventional Tyvek 1422-A. Significantly better performance was observed for higher air permeability ensembles made of SMS and SBPP. The tightly woven polyester ensemble was not statistically different from either group.

The roles of moisture vapor transmission rate and air permeability for each fabric were examined as possible predictors of fabric performance. Air permeability appears to be a better predictor of ensemble performance than MVTR. Participants in garments with higher air permeability were able to sustain higher treadmill speeds and higher metabolic rates than those in clothing conditions with lower air permeability. Based on approximate extrapolations to the semiclothed condition, it appeared that a coverall made from a fabric with an air permeability on the order of 10,000 L/min^{-1}/cm^{-2}/bar^{-1} would not limit evaporative cooling during work.

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