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Thermal protective performance of protective clothing used for low radiant heat protection

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Abstract

A laboratory simulation was performed to study the thermal protective performance of fabric systems under low level thermal hazards in the range of 6.3–8.3 kW/m^2. Two approaches were used. The first used a method similar to the ASTM F 1939, radiant heat resistance test, while the second used a modification designed to capture the contribution to skin burn injury due to energy stored in the test specimens being released after the direct exposure had ended. Both dry and wet specimens were tested. In order to accommodate the prolonged exposure time a water cooled heat flux sensor was used to calibrate the radiant heat source and measure the energy directly transmitted through during the exposure and discharged later from the fabric systems. The Henriques Burn Integral (HBI) was adopted and programmed with a three layer skin model to predict the time required to achieve a second degree skin burn injury. The study investigated the thermal protection provided by the clothing with different layering and examined the effect of moisture under low level radiant heat exposures. In addition, the physiological burden associated with wearing the clothing was predicted and compared. The results obtained show the difference in measured protection level under low radiant heat from these two approaches and demonstrate that the stored thermal energy released from the clothing system significantly lowers the measured thermal protective performance.

Keywords

Low radiation, burn injury, thermal hazards, protective clothing

Introduction

Thermal protective clothing is primarily designed to provide protection from thermal hazards which include exposure to high temperature radiant sources, flame impingement, hot liquids and gases, molten substances, hot solids and surfaces. It is difficult to completely define the nature and characteristics of these thermal hazards, because of the many environmental and physical factors involved. Three general categories are used to identify common thermal environmental conditions. These are routine, hazardous, and emergency.[1–3] Heat transfer from the thermal hazards can be by radiation, convection or conduction, or a combination.

A great amount of research has been performed on emergency conditions.[4–9] These conditions are characterized by high intensity, short duration exposures. The exposure level among these emergency conditions ranges from 20–160 kW/m^2 and can be encountered during large fires and explosions. Severe thermal problems and life threatening injuries are associated with these conditions. For the existing protective clothing, the tolerance time for people in these exposures is in the range of 5 to 20 seconds.[3] Barker, Shalev and Lee[4,6,7] have reported extensively on the use of the TPP (NFPA 1971) test to understand the thermal response of single layered fabrics in high heat exposures. The research demonstrated that changes in exposure intensity and

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the mix of radiant to convective heat transfer at the specimen surface, and the fabric properties affected the overall thermal protective performance. Radiant protective performance of single layer fabrics has been assessed using a RPP tester by Sun.[5] The results showed that the thermal resistance of the fabrics was fundamentally related to chemical and physical structures of fabrics. In Sun's study, some physical properties, such as evaporative resistance, wicking ability, relevant to comfort were also examined and their relations to fiber type, thickness and layering were explored.

Studies of protection of clothing systems under flash fire exposures were conducted using instrumented flash fire manikin evaluation systems.[8,9] The study performed by Crown et al. showed that style, fit and closure system all affected the thermal protection provided by flightsuits.[8] Song developed a numerical model for simulating the flash fire manikin evaluation system. The heat transfer from the simulated flash fire, the clothing system and the air gap between clothing and manikin body were characterized and the clothing performance was predicted under the flash fire exposure conditions.[9] These latter studies indicated that the air gap developed between the clothing and the human body plays a critical role in the thermal protective performance under the intense exposure conditions. In the early 1970s, Perkins performed studies on heat transfer values of some single layer fabrics when exposed on low radiation thermal hazards. The retention of the integrity for these fabrics under various heat intensities was also examined.[10] Perkins study showed the effect of fabric weight on the protection provided by the fabric under low flux level exposure and some characteristics demonstrated from exposure to high level heat flux.

Thermal radiation exposure is frequently encountered among all the thermal hazards, especially in routine and hazardous conditions. Exposure to low level thermal radiation ranging from $5\,kW/m^2$ to $20\,kW/m^2$ is one of the most common thermal hazards that could cause skin burn injuries.[3] Data produced by decades of fire research on structural fires shows that most burn injuries sustained by firefighters occurred in the low level thermal environments.[11,12] Firefighters can receive burns in thermal exposures that are considerably lower than flashover conditions. These burns occur as a result of prolonged exposure in thermal environments classified as routine or hazardous conditions. These exposures are usually several minutes in duration, and the exposure levels are generally not sufficient to degrade the turnout shell fabric. The energy stored in the fabric system during the exposure can contribute to skin burn injury due to the discharge after the exposure and the presence of the moisture could significantly change the thermal protective performance.[13]

Several prominent issues that remain in the area of protective clothing that may affect the overall clothing performance are the moisture in the clothing, stored thermal energy and heat stress applied when wearing the clothing. The presence of moisture in clothing systems is common and has a complex effect on clothing thermal protective performance. There have been extensive studies on the effects of moisture in protective clothing.[14–17] The moisture distribution and the quantity, the structure of fabric system and exposure intensity each affect clothing thermal protective performance. Accumulated moisture in fabrics or fabric systems influences the thermal properties and changes the heat transfer characteristics. When a garment is exposed to thermal hazards, either low or high intensity, the mechanisms associated with heat and mass transfer, energy storage and moisture phase change (which could potentially cause 'steam burns') become extremely complicated as they are interconnected. This is extremely important when the protective clothing is thick or multi-layered. Normally thick fabrics and fabric systems provide better thermal insulation, but they also store a greater amount of thermal energy which could discharge after the exposure.[13] The energy stored within the garment system can be discharged naturally or by compression of the garment due to motion or contact with a solid object. The discharge of this stored energy after an exposure can cause or increase a burn injury. Heat stress associated with wearing protective clothing is a topic of active research. Normally the protective clothing, while providing protection against hazards, impedes heat and moisture exchange between the human body and environment and therefore affects achieving a human comfort balance. As a result, an added physiological load is generated and wearers' performance is significantly reduced, particularly in a hot environment.[18,19] Effective protective clothing should minimize heat stress while providing protection. The impact of protective clothing on heat stress depends on the extent to which the clothing affects the heat and moisture transfer between the wearer and the environment. The two main properties of the clothing which affect the thermal balance between the wearer and environment are the thermal resistance (R_{ct}) and the evaporative resistance (R_{et}).

Only a few studies have been conducted on thermal protective performance with prolonged exposure to low level radiant heat, the effect of absorbed energy and moisture contained in fabric systems on burn protection in these conditions. Lack of full understanding of the performance of thermal protective clothing exposed to low level radiation and of the relevant contributing parameters associated with clothing is the main factor that contributes to develop skin burn injuries. In this study, a laboratory simulation of a low intensity thermal hazard was developed that aimed to evaluate the thermal protective performance of protective clothing that were made of different fabric systems. Two approaches were used. The first used a method similar to the ASTM Standard Test Method for Radiant Heat Resistance of Flame Resistant Clothing Materials, while the second used a modification designed to capture the contribution to skin burn injury due to energy stored in the test specimens being released after the direct exposure had ended. The traditional TPP/RPP (applied in NFPA 1971 and ASTM F 1939) approach and a stored-energy approach were applied and the results obtained were compared and analyzed. The study includes the examination of the performance provided under low level thermal radiation in standard as well as wet conditions. The effect of methods, moisture and different layering were analyzed. The physiological burden that would be applied to the wearer was estimated by measuring thermal resistance, evaporative resistance and total heat loss (THL). The technical data generated under these laboratory simulations will facilitate selection of appropriate protective clothing systems to prevent thermal injuries under the specified thermal hazards while minimizing heat strain at work. The criteria for these protective system selections will be a balance of maximizing protective performance and minimizing heat strain when wearing these protective systems.

Experimental

Fabric Materials

The selected fabrics and their technical properties are provided in Table 1. The fabrics were chosen to include commercially available, commonly used, and high performance fabrics in the thermal protective clothing field. Several protective fabric systems were constructed with expected different levels of protective performance. The fabric systems were constructed as single layer fabric (used for coveralls), two layer systems, and multilayer composite systems. The purpose of these fabric systems was to represent actual protective garments worn by industrial workers, firefighters, and military personnel, etc. Fabrics commonly used for underwear, wool and Carbon X (an oxidized polyacrylonitrile blend), were incorporated in some of these fabric systems and evaluated as a whole system. The details of the fabric system construction and physical properties are described in Table 2. No air permeability was observed in fabric systems B-4, B-5, and B-6 due to the incorporation of a membrane in these systems.

Test Apparatus and Methods

A test apparatus was developed to perform the laboratory simulation of low level radiant thermal hazards. Quartz tubes were employed as the radiant heat source as specified in ASTM F 1939 for measuring radiant heat resistance. The quartz tubes were positioned horizontally and electronically regulated to deliver the specified heat flux. To accommodate the long exposure durations a water cooled Schmidt-Boelter heat flux gauge was chosen to calibrate the heat source and measure the heat flux transmitted and discharged through the fabric systems. The sensor was secured in an insulating block and attached to the sample holder with the sensor located in a central position as illustrated in Figure 1. A protective shutter was placed between the radiant energy source and the specimen. The protective shutter was used to block the radiant energy prior to the exposure of a specimen and to control the exposure time. The test apparatus, which includes the radiant heat source, specimen holder, water cooled sensor, data acquisition system, and programmed skin burn prediction software, is illustrated in Figure 2. The heat flux readings from the sensor were recorded by the computer and applied to predict second degree skin burn injury. The details of the method used for skin burn injury calculation are described in ASTM F

Table 1. Structural features of selected fabrics

Fabric code	Fiber content	Weave type	Weight (g/m^2)
Fabric A	60% Lenzing FR®/40% Kevlar®	Twill	305
Fabric B	100% Nomex®	Plain weave	180
Fabric D	100% Nomex®	Plain weave	108
Thermal barrier A	100% Nomex®	Fleece napped both sides	257
Thermal barrier B	100% Nomex®	Nonwoven, stitch laminated with moisture barrier	481
Thermal barrier C	100% Nomex®	Quilted	339
Inner wear fabric A	100% Wool	Jersey interlock knit	288
Inner wear fabric B	100% CarbonX®	Jersey interlock knit	261

Table 2. Structural features and physical properties of fabric systems

Assemble code	Fabric assembly description	Thickness, mm	Weight (g/m^2)	Air permeability ($cm^3/s/cm^2$)
A-1	Fabric A	0.51	305	5.4
A-2	Fabric A + thermal barrier A	5.46	562	5.5
A-3	Fabric A + thermal barrier A + inner wear fabric A	6.80	850	5.2
A-4	Fabric A + thermal barrier A + inner wear fabric B	6.70	823	5.4
B-1	Fabric B + fabric D + inner wear fabric B	2.05	549	27.5
B-2	Fabric B + fabric D + thermal barrier A	5.63	545	25.8
B-3	Fabric B + fabric D + fabric B + thermal barrier C	4.33	779	23.2
B-4	Fabric B + thermal barrier B	4.87	661	0
B-5	Fabric B + thermal barrier B + inner wear fabric B	6.10	922	0
B-6	Fabric B + thermal barrier B + thermal barrier A	8.33	918	0

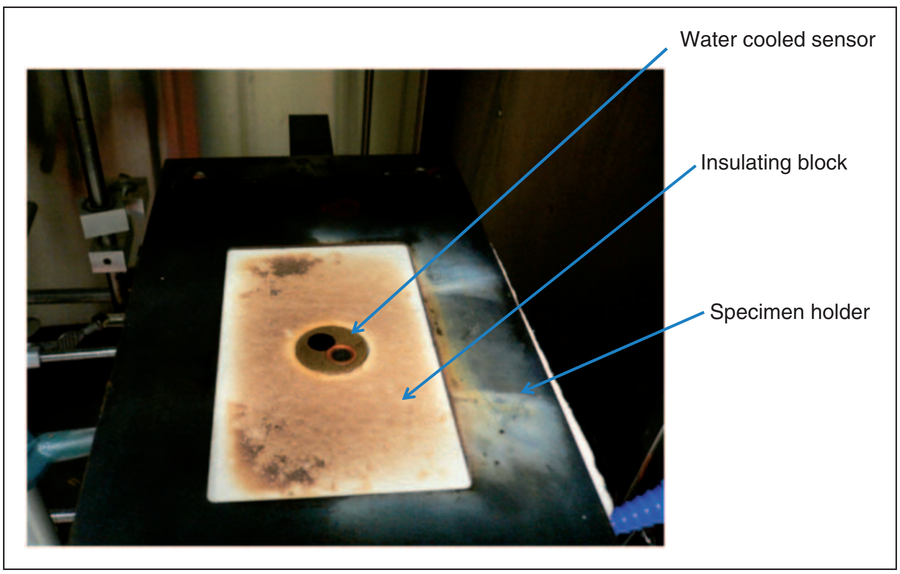

Figure 1. Specimen holder and water cooled sensor used in the apparatus.

1930-00, Standard Test Method for Evaluation of Flame Resistant Clothing for Protection Against Flash Fire Simulations Using an Instrumented Manikin. As the exposure level applied in this study is low, the blood effect on heat transfer in human skin was considered. The governing equation for heat transfer in skin model is described as:

$$(\rho c_p)_s \frac{\partial T}{\partial t} = k_s \frac{\partial^2 T}{\partial x^2} + (\rho c_p)_b \omega_b (T_a - T) \qquad (1)$$

In this equation, $(\rho c_p)_s$ and k_s are the volumetric heat capacity and thermal conductivity of human tissue and $(\rho c_p)_b$ is the volumetric heat capacity of blood. ω_b is the rate of blood perfusion and is taken to be $0.00125\,m^3{}_{blood}/(s\cdot m^3{}_{tissue})$ for the dermis and subcutaneous, and $0.0\,m^3{}_{blood}/(s\cdot m^3{}_{tissue})$ for the epidermis. The boundary condition at the base of the subcutaneous layer is set at a constant temperature of 37 °C and the boundary condition on the skin surface is set to be the time varying heat flux acquired from the experiment. The tissue temperature is assumed to initially vary as a linear function of depth into the skin, from a surface temperature of 34 °C to the subcutaneous base temperature of 37 °C. The skin layer properties and parameters used in the skin model are provided in Table 3.

Two test approaches were applied in the research to assess the thermal protective performance of the selected fabric systems: the first is the traditional TPP/RPP approach, which considers only energy transferred through the fabric system during the exposure to the heat source. This approach is used in the NFPA 1971 TPP test and the ASTM F 1939 Standard Test Method for Radiant Heat Resistance of Flame Resistant Clothing Materials. The second approach is

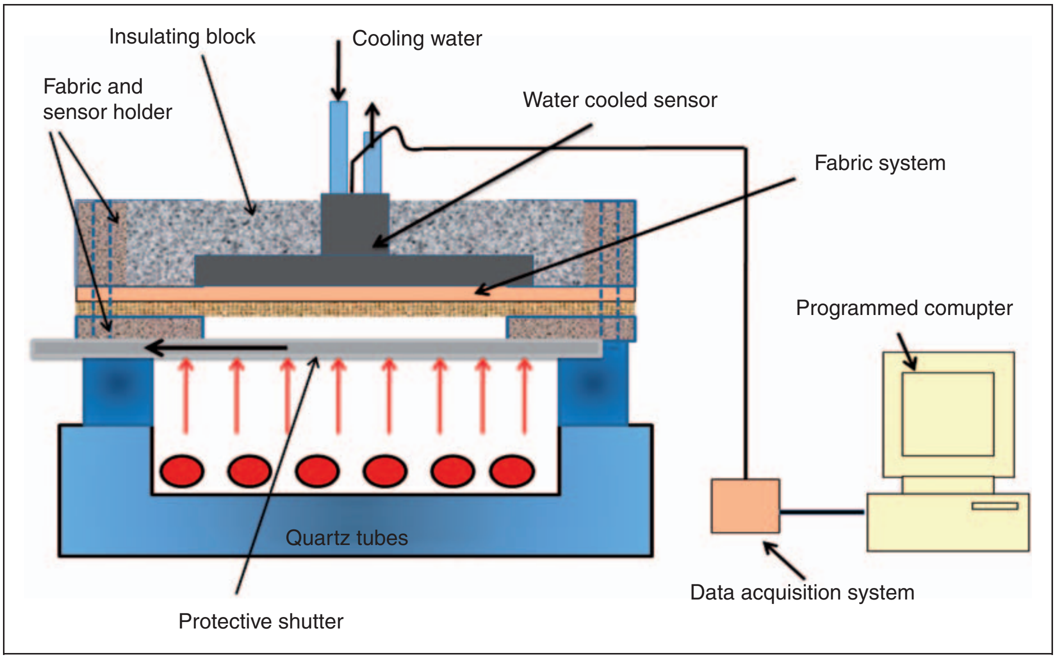

Figure 2. Schematic diagram of apparatus used to measure thermal protective performance.

Table 3. Thermal properties used in the skin model

Human skin/thermal properties		Value
Epidermis	Thermal conductivity (W/m·°C)	0.255
	Thickness (m)	8.0×10^{-5}
	Volumetric heat capacity (kJ/m^3·°C)	4320
Dermis	Thermal conductivity (W/m·°C)	0.523
	Thickness (m)	2.0×10^{-3}
	Volumetric heat capacity (kJ/m^3·°C)	4080
Subcutaneous	Thermal conductivity (W/m·°C)	0.167
	Thickness (m)	1.0×10^{-2}
	Volumetric heat capacity (kJ/m^3·°C)	3060
Blood	Volumetric heat capacity (kJ/m^3·°C)	3996

the stored-energy approach, which accounts for the thermal energy contained in the exposed test specimen after the exposure. The thermal stored-energy approach was designed to measure the total energy delivered to the sensor from the combination of directly transmitted energy during the exposure and the subsequent discharge of energy stored in the fabric system after the thermal exposure. The discharge of the stored energy after the exposure can contribute to skin burn injuries.[13] The comparison of the two approaches is illustrated in Figure 3. In the TPP/RPP approach, the total energy delivered to the sensor comes from that transmitted during the exposure and accumulates to such an amount that could develop a skin burn injury. In the stored-energy approach, however, the total energy that generates a skin burn injury consists of energy transmitted during exposure and the energy discharged in the cooling period. Normally in the stored-energy approach a shorter exposure time is necessary to produce a predicted burn injury.

The test and calculation procedure are summarized and shown schematically in Figure 3 and Figure 4. For burn time predicted from TPP/RPP approach, the specimens were exposed to 300 seconds and the measured heat flux as a function of time from the sensor was obtained. The HBI method was then evaluated as a function of time to identify the time ($t_{TPP/RPP}$) when $\Omega = 1.0$, the onset of a second degree skin burn injury. Based on the predicted second degree burn time, a total energy required to generate a second degree skin burn was calculated, noted as ΔE_T. With the stored-energy procedure two steps were applied: an exposure step and a cooling step. First the specimens were exposed to the energy source for the selected exposure time ($t_{TPP/RPP}$). The exposure time ($t_{TPP/RPP}$) is the skin burn time predicted from the TPP/RPP approach described above. At the end of the exposure period, the specimens were isolated from the heat source (protective shutter closed) and data acquisition was continued for 60 seconds. The measured heat flux as a function of time is obtained and applied to calculate the total energy required to generate a second degree burn, ΔE_T, and the energy discharged during the cooling period, noted as ΔE_{cool}. This energy (ΔE_{cool}) captured during the cooling period is the amount of the energy released from stored energy in fabric systems. Base on the heat flux function obtained, the energy that must be transmitted to the sensor during the exposure in order to cause a

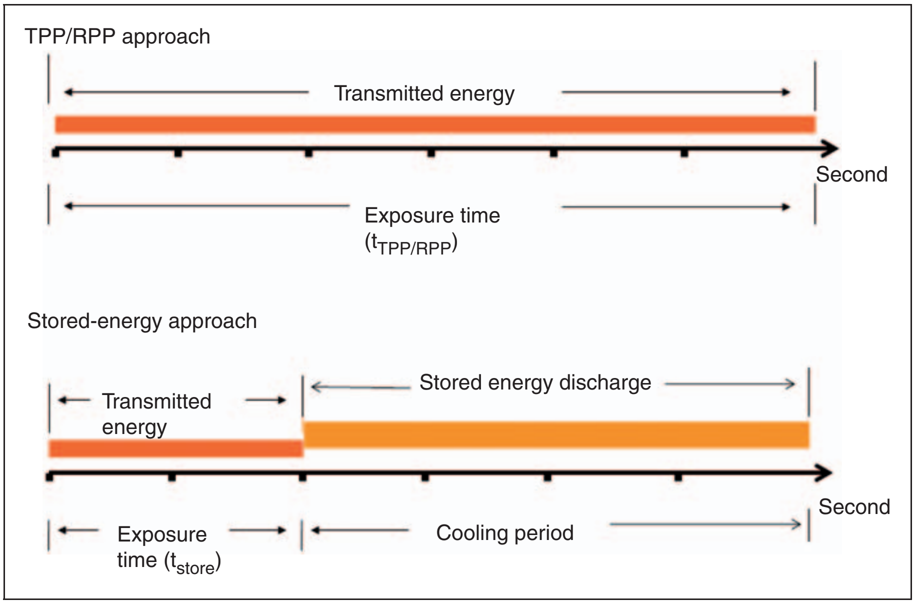

Figure 3. Comparison of the TPP/RPP and stored energy approach.

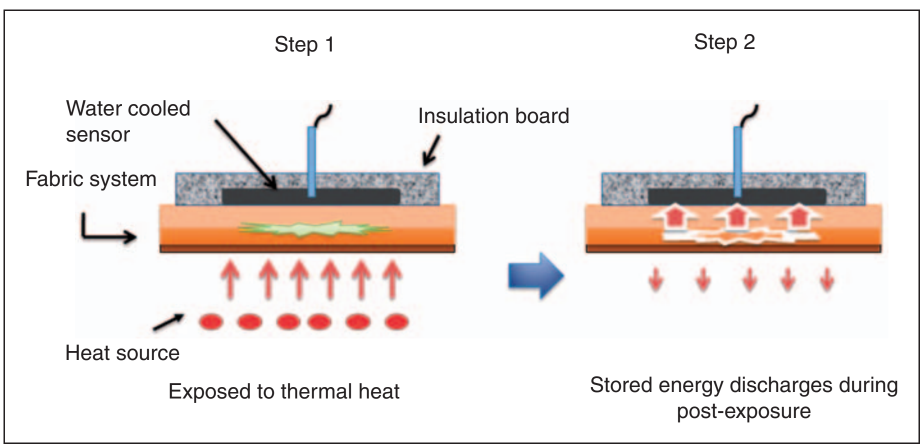

Figure 4. Stored-energy test schematic procedure for data collection.

second degree burn, noted as ΔE_{SE}, is calculated by $\Delta E_{SE} = \Delta E_T - \Delta E_{cool}$. Given the known energy ΔE_{SE}, the time corresponding to ΔE_{SE} from the generated heat flux function was identified, which is the Minimum Exposure Time (MET) to generate a second degree skin burn that considers the energy storage contribution during cooling period. The relations of ΔE_T, ΔE_{SE} and ΔE_{cool} are illustrated in Figure 5. The calculated MET was compared with the MET determined using an iterative method (without compression) as described in Song's study[13] and the results show a good agreement.

Test Conditions

Three levels of radiant heat exposure were simulated for evaluating the selected clothing systems, these were 6.3 kW/m^2, 7.5 kW/m^2 and 8.3 kW/m^2. The intensity of the exposures was chosen to be representative of the most common fireground conditions.[12,20] In order to examine the effect of moisture on the performance of the fabric systems under these low radiant heat exposures, a preconditioning protocol was selected to moisten them. The specimens were first conditioned in the standard atmosphere for 24 hours prior to moisture application and testing. Appropriate layers were saturated with moisture following a modified ASTM D 461: Standard Test Method for Felts, Section 17. Specimens were immersed in water for a minimum of 1 min, then removed from the water and placed between sheets of commercial blotting paper and rolled once over with a 1000 g metal roller to remove excess moisture. The moisture content by weight obtained by using the preconditioning protocol was around 15–70%, depending on the nature of the layers in the composite.

Protective Clothing Physiological Burden Estimation

In this research, the thermal resistance (R_{ct}) and the evaporative resistance (R_{et}) of each fabric system were measured according to ASTM F 1868, Standard Test Method for Thermal and Evaporative Resistance of Clothing Materials Using a Sweating Hot Plate, Procedure Part C – Total Heat Loss in a Standard Environment. The *Total Heat Loss* (*THL*) was calculated from the equation given below, where, Q_t is total heat loss, R_{cf} is average intrinsic thermal resistance of the specimen and R_{ef} *is* average apparent intrinsic evaporative resistance of the sample. Three specimens were tested for each sample:

$$Q_t = \frac{10^\circ C}{R_{cf} + 0.04\,K \cdot m^2 \cdot W^{-1}} + \frac{3.57\,kPa}{R_{ef} + .0035\,kPa \cdot m^2 \cdot W^{-1}} \tag{2}$$

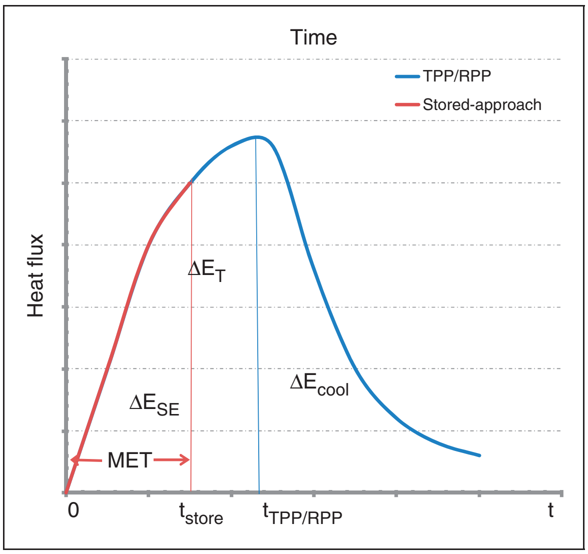

Figure 5. Schematic of heat flux profiles for TPP/RPP approach and stored-energy approach.

Results and Discussion

The data obtained using the traditional TPP/RPP approach under the three radiant heat exposures in both standard and wet conditions are described in Table 4 and Table 5. The predicted second degree burn time was based on the average of the three tests for each fabric system.

The measured protection level afforded by selected fabric systems varied, from 45 seconds to more than 3 minutes or even no prediction of skin burn under these three low level heat exposures. In these low intensity heat exposures no obvious degradation or damage was observed on the outer fabric, which was exposed directly to the thermal hazard. The burns predicted occur as a result of thermal energy transmitted through the fabric system and the energy accumulated to the shell fabric is not sufficient to degrade the fabric.

Table 4. Predicted time required to generate second degree skin burn using the TPP/RPP approach in standard conditions*

Fabric assembly	Predicted burn time (time to second degree skin burn, in seconds)		
	8.3 (kW/m^2) (SD)	7.5 (kW/m^2) (SD)	6.3 (kW/m^2) (SD)
A-1	45.4 (0.8)	50.2 (0.4)	64.3 (1.6)
A-2	124.6 (0.6)	135.1 (0.4)	162.0 (3.4)
A-3	137.4 (2.5)	152.2 (3.8)	176.4 (2.2)
A-4	151.5 (2.9)	155.6 (1.6)	188.3 (3.2)
B-1	79.7 (1.5)	88.5 (1.3)	115.6 (1.8)
B-2	122.4 (2.1)	132.2 (2.4)	176.8 (3.0)
B-3	148 (2.8)	156.1 (2.7)	215.6 (3.5)
B-4	127.4 (1.8)	134.6 (1.5)	180 (2.4)
B-5	146.9 (2.3)	161.5 (3.2)	204.5 (2.6)
B-6	192.5 (2.1)	205.9 (2.4)	No burn

*standard condition, specimen was preconditioned for 24 hours and tested under standard atmosphere; SD, standard deviation.

Table 5. Moisture content in fabric system

Fabric system	A-1	A-2	A-3	A-4	B-1	B-2	B-3	B-4	B-5	B-6
Moisture content (MC, %)	15.4	66.9	65.2	63.3	28.8	68.2	62.5	63.1	67.2	68.8

The lowest protection times were observed on the thinnest fabric systems, in particular the single layer systems. With one layer of fabric, the protection time was predicted to be around 45 to 64 seconds under these low intensity radiant heat exposures. The observed difference in protection time between 8.3 kW/m^2 and 6.3 kW/m^2 exposures was about 20 seconds. As more layers were added to the system, the thermal protective performance increased significantly, specifically the addition of a thermal barrier (insulation) layer, as shown in A-3, A-4, B-5 and B-6. For system B-6, the protection time was predicted to be more than 3 minutes for exposures of 8.3 and 7.5 kW/m^2, and no burn was predicted for a 6.3 kW/m^2 exposure. The observed difference of the predicted second degree skin burn time in multilayer systems between 8.3 and 6.3 kW/m^2 exposures was up to 58 seconds. The structure of multi-layer fabric systems increase the overall thickness of the assembly, and consequently protection against low level radiant heat exposure improves significantly.

The effects of fabric thickness and exposure intensity on thermal protective performance are summarized in Figure 6. The overall trend obtained from the low intensity exposures demonstrated that the thickness of the fabric and fabric system is a primary factor that affects thermal protective performance, which is consistent with the results of previous research.[13,21] The increasing thickness that results from addition of layers provides more space for still air or dead air and therefore more resistance to heat transfer than thinner fabric systems. The increase of still air or an air layer in the fabric system provided by layering is more efficient at reducing the heat transfer than by the fabric structure itself. Comparing the results of A-2 and A-4 in Table 4 demonstrates the effect of the addition of single inner-wear fabrics, in this case high quality wool or oxidized polyacrylonitrile based fabric, increases the protection time significantly during these exposures.

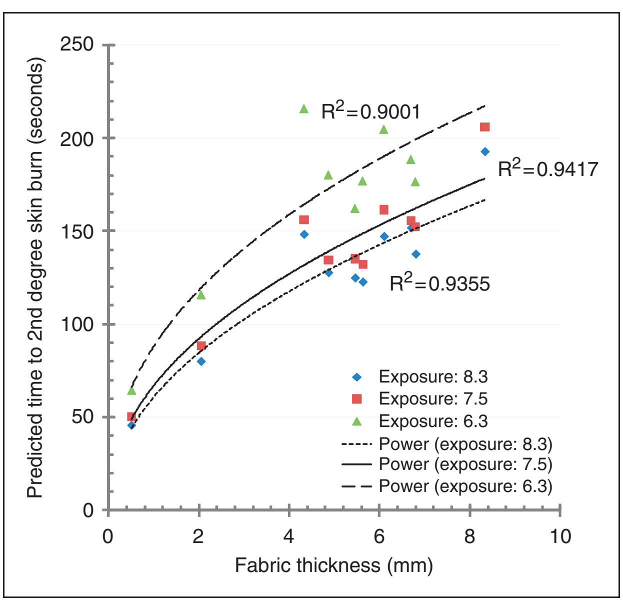

Figure 6. Effect of fabric system thickness on predicted skin burn time under different exposure level. Power represents a power regression for selected data series.

Additionally for thicker fabric systems such as A-4 and B-6, the difference in predicted protection time for second degree skin burn among these three exposures is larger than that for single or thinner fabric systems. This phenomenon is thought to be associated with the different amount of air trapped in the fabric system and therefore the heat transfer mechanism involved may be different.

In order to study the effect of the moisture on thermal protective performance under these low level exposures, moisture was added to the fabric systems. Table 5 shows the moisture content following the wetting protocol as described in the Test conditions section. The moisture content obtained ranges from 15% to 69%. The one layer fabric contained less and multilayer fabric system with thermal barrier gained 60–70%.

In Table 6 the predicted burn times for these fabric systems are presented. The overall trends exhibited from the moist systems are similar to those in standard conditions, but the predicted protection time is increased for most of the fabric systems. The increase in predicted burn time indicates the moisture in clothing systems enhances the protective performance under these continuous low level radiant heat exposures, with some exceptions in B fabric assemblies. For the single layer fabric the increase in predicted burn time is approximately 5–17 seconds, and in thicker systems, such as A-4 and B-6, the predicted burn time increase is approximately 77–83 seconds.

The relation of the exposure level, fabric thickness and predicted time to second degree skin burn for moist fabric systems are illustrated in Figure 7. With increasing fabric thickness, the thermal protective performance indicated by predicted skin burn time improves and the difference in skin burn time predicted between the exposure levels increases. The predicted skin burn times for these fabric systems obtained in standard and wet conditions are compared in Figure 8 for the 7.5 kW/m^2 exposure. The majority of the tested fabric systems showed an increased predicted time to skin burn in the wet conditions when compared to the dry conditions. Systems which exhibited a decrease in predicted skin burn time in the wet condition are those which had fabric B as an outer layer and overall system density of more than 150 kg/m^3. Both effects are due to the amount of moisture contained and its

Table 6. Predicted time required to generate second degree skin burn using TPP/RPP approach in wet conditions

Fabric assembly	Predicted burn time (time to second degree skin burn, in seconds)		
	8.3 (kW/m^2) (SD)	7.5 (kW/m^2) (SD)	6.3 (kW/m^2) (SD)
A-1	51.7 (0.4)	59.9 (1.2)	80.6 (2.8)
A-2	133 (2.3)	146.9 (1.8)	174.1 (2.9)
A-3	132.4 (1.3)	165.6 (2.1)	199.2 (3.2)
A-4	171.6 (1.8)	167.6 (2.7)	195.1 (3.8)
B-1	67.8 (0.9)	76.5 (0.4)	88.8 (1.2)
B-2	155.7 (2.9)	159.7 (3.0)	255.2 (4.2)
B-3	137 (2.6)	151 (1.8)	177.5 (2.0)
B-4	149.9 (2.9)	161.2 (3.8)	181 (4.5)
B-5	136.1 (3.7)	147.5 (3.2)	192.3 (2.6)
B-6	270 (3.4)	289 (4.3)	No burn

SD, standard deviation.

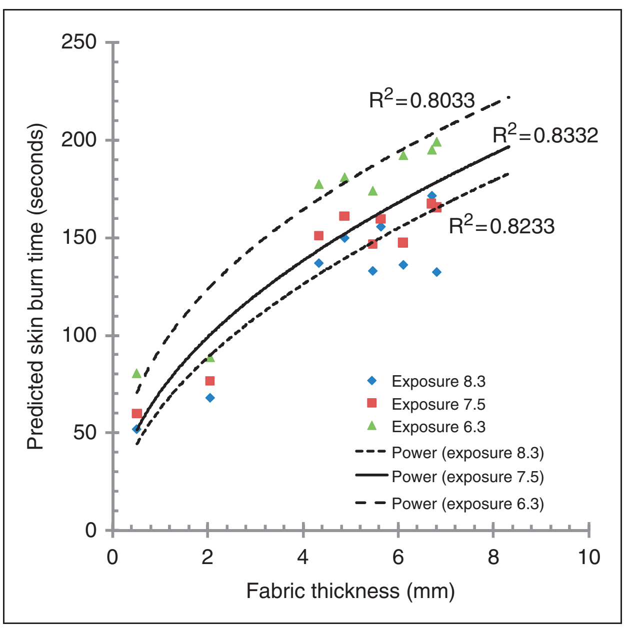

Figure 7. Effect of fabric system thickness on predicted skin burn time in wet condition. Power represents a power regression for selected data series.

distribution in the fabric system. The results obtained in these low intensity exposures demonstrate the complex influence of the moisture on heat transmission in fabric systems and potential for skin burn injuries.

Table 7 presents the results that were predicted by considering the thermal energy contained in an exposed test specimen (thermal stored energy) after the radiant heat exposure has ceased. The thermal stored energy contributes to skin burn injury by discharging during the cooling period (post exposure). Comparing these results with those in Table 4, the significant differences in predicted burn time were observed between the TPP/RPP and stored-energy approaches. Generally lower exposure times were predicted for all these fabric systems due to the discharge from stored energy in fabric system. The single fabric shows protection times in the range of 30 to 50 seconds, which are 20 to 30 seconds lower than predicted using the TPP/RPP approach. For thicker systems, however, a large difference in predicted protection time between the two approaches was observed. As thickness of fabric system increases the heat capacity of the system increases due to the added mass and, as a result, a large amount of thermal energy can be stored during the exposure. The discharge, when delivered after an exposure and combined with the energy transmitted during the exposure, can cause skin burn injuries. A comparison of predicted exposure times necessary to cause a burn injury obtained from the TPP/RPP and stored energy approaches is illustrated in Figure 9. The results show that the difference in burn time predicted by these two approaches becomes larger when the thickness of the fabric system increases. The change in time indicates thicker systems can store more energy than thinner systems or single layer fabrics and as a result a large amount of energy may discharge after exposure and contribute to skin burn injuries.

In order to estimate the physiological burden associated with wearing these clothing systems, two thermal properties for these fabric systems were measured using a sweating guarded hotplate following ASTM F 1861, Standard Test Method for Thermal and Evaporative Resistance of Clothing Materials Using a Sweating Hot Plate. The intrinsic thermal resistance (R_{cf}) and intrinsic evaporative resistance (R_{ef}) are the two main values that give a quantitative assessment of the heat and moisture transfer of a fabric system for use in protective clothing. The higher the thermal resistance value, the more thermal protection is

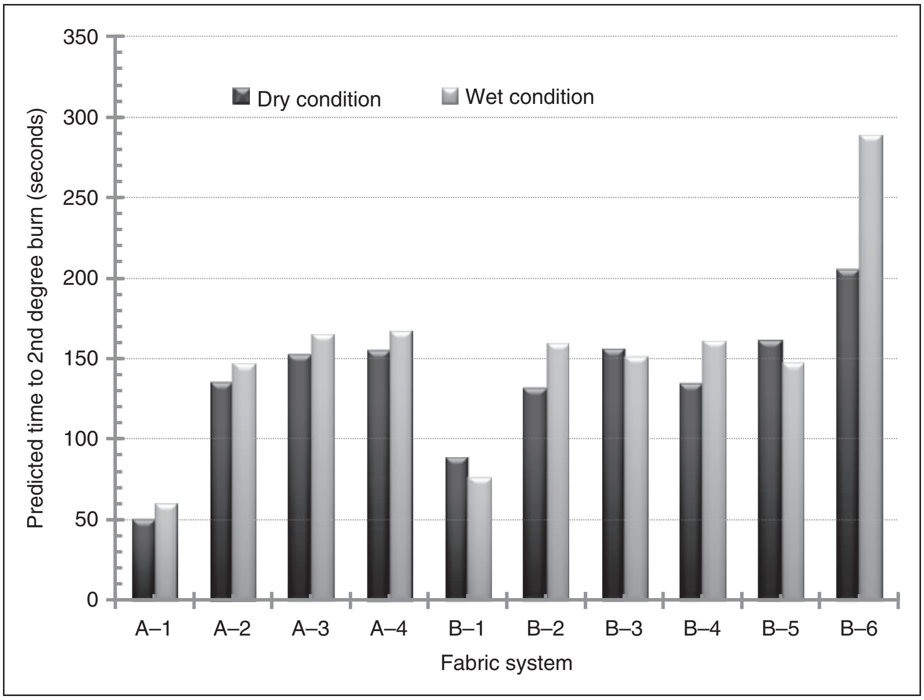

Figure 8. Comparison of predicted time to second degree skin burn in standard and wet conditions when exposed to 7.5 kW/m^2.

Table 7. Predicted minimum exposure time (MET) required to generate second degree skin burn using stored-energy approach in standard conditions

Fabric assembly	Predicted burn time (time to second degree skin burn, in seconds)		
	8.3 (kW/m^2) (SD)	7.5 (kW/m^2) (SD)	6.3 (kW/m^2) (SD)
A-1	29.8 (1.4)	35.9 (0.9)	50.1 (1.4)
A-2	100 (0.4)	109.9 (0.6)	136.9 (3.3)
A-3	111 (2.8)	125.2 (3.5)	150.1 (3.9)
A-4	124.2 (2.7)	128.6 (1.2)	160.6 (4.2)
B-1	60.7 (1.2)	68.5 (0.8)	95.1 (1.8)
B-2	97.5 (1.8)	104.2 (2.3)	136 (3.7)
B-3	122.5 (2.1)	130.3 (2.6)	146 (3.2)
B-4	105 (1.6)	106 (3.0)	133 (3.8)
B-5	121.7 (1.4)	135.5 (2.8)	156.4 (2.6)
B-6	172 (0.9)	173 (1.9)	219 (3.5)

SD, represents standard deviation.

provided to the wearer. However, for a person working in a hot environment, evaporation of sweat becomes an important means of heat loss. In addition, dry heat loss decreases with increasing ambient temperature, while evaporative heat loss (cooling) increases. Consequently, at high activity levels and/or in hot environments, the thermal resistance value alone is insufficient for characterizing and comparing fabric and clothing systems. The resistance to evaporative heat transfer (R_{ef}) also needs to be determined for the fabric system. This is because materials used in protective clothing often impede the transfer of moisture reducing the body's ability to cool itself through the evaporation of sweat. As a result a physiological strain can be developed. Based on the fact that these two factors affect heat and moisture balance between the human body and its environment a THL index was developed that combines these two factors to address the potential heat stress associated with wearing clothing.[22] These three parameters are thought to be fundamental in assessing clothing comfort, especially for protective clothing.

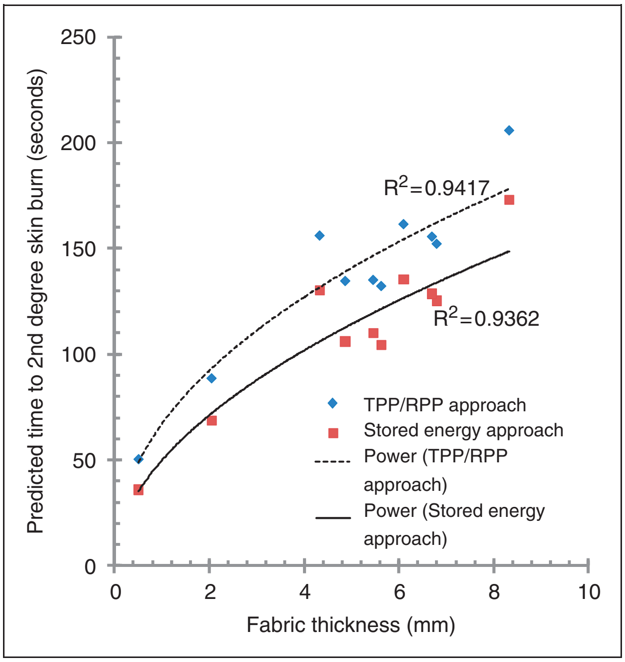

Figure 9. Comparison of predicted burn time from TPP/RPP to MET for stored energy at exposure of 7.5 kW/m^2. Power represents power regression for selected data series.

Table 8. Measured thermal resistance, evaporative resistance and total heat loss (THL) for fabric systems

Fabric assembly	Thermal resistance, R_{cf} (K·m^2/W)	Evaporative resistance, R_{ef} ($\times 10^{-3}$ kPa·m^2/W)	Total heat loss (THL) (W/m^2)
A-1	0.017	3.8	663
A-2	0.204	20.6	189
A-3	0.202	24.1	171
A-4	0.205	24.2	169
B-1	0.074	9.9	353
B-2	0.172	20.4	197
B-3	0.191	21.8	185
B-4	0.184	21.6	187
B-5	0.192	26.2	163
B-6	0.280	47.9	101

The thermal resistance (R_{cf}), evaporative resistance (R_{ef}), and the calculated THL value for the selected fabric systems are provided in Table 8 and the relationship between THL and fabric system thickness is illustrated in Figure 10. Polynomial regression curves were obtained and these curves (Figure 10) present a high correlation coefficient which indicates a good fit for the selected data. Lower values for thermal and evaporative resistance, and thus higher THL values, were measured for single layer fabrics and thin fabric systems. As the thickness of the fabric system is increased, as illustrated in Figure 10, a significant increase in both thermal resistance and evaporative resistance was observed. This was most notable between the thicknesses of 0.5 mm and 4 mm, which is also a change from a one layer system to a three layer system. The major factors that contribute to thermal resistance are the still air trapped in the fabric and, in multi-layer systems, the size of air layers developed between fabric layers. For evaporative resistance the pore size of the fabrics and the thickness of the still air layers developed between fabric layers are the critical factors. For most fabrics the evaporative resistance is minimal and quite similar, because the pore size for most fabrics is large enough for moisture to pass through. With the addition of a membrane, the evaporative resistance could be quite different, which depends on the nature of the membrane. For a system with an impermeable or less permeable membrane, the evaporative resistance is huge, and the THL value could be quite low regardless of the thickness. The addition of a moisture barrier has a large effect on evaporative resistance, and thus THL. A significant change in both the thermal and evaporative resistance can be expected when the thickness of the fabric system increases as a result of more layers being involved. However, in the curves shown in Figure 10, a plateau was observed which indicates both thermal and evaporative resistances do not show an immediate change as thickness increases. These thicknesses, in the range of 4 mm to 6.5 mm, are typically the three layer fabric systems. This implies that fabric system structure is a key factor and the thickness of the system is less pronounced. The phenomena observed is thought to be associated with still air trapped between the layers that dominates both heat and moisture transfer through the system.

Generally, the higher the THL, the more likely the system will be able to dissipate excess body heat. Higher THL values are created by lighter, thinner thermal liners and shell fabrics, but most effectively by high performance membranes. Garments with impermeable moisture barriers or thicker and heavier thermal insulation layers will inhibit total heat loss and develop heat stress to extreme levels. The B-6 system presents both a high thermal insulation value and high evaporative resistance and, accordingly, a low total heat loss. Thus, even though the predicted thermal protection performance is high, the heat stress experienced by wearing this clothing ensemble will likely be high as well.

Summary and Conclusions

The thermal protective performance of different fabrics and fabric systems were evaluated during exposure to low levels of radiant heat flux. The present findings demonstrated that even for a low level thermal radiant

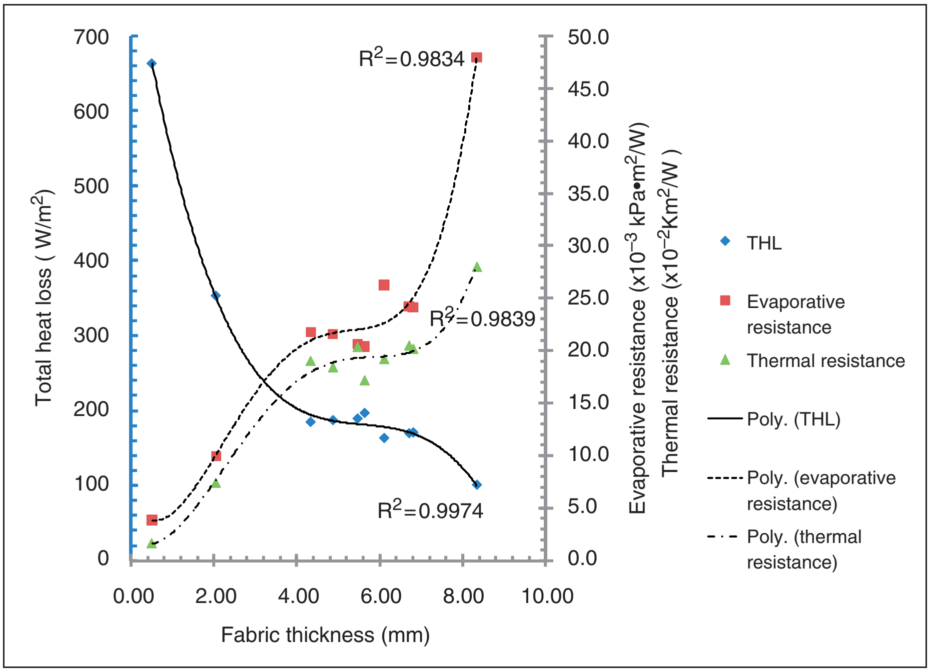

Figure 10. The effect of fabric thickness on thermal resistance, evaporative resistance and total heat loss. Poly. represents a polynomial regression for selected data series.

hazard, ranging from 6.3 to 8.3 kW/m^2, a typical three layer thermal protective clothing system is required to protect the wearer from skin burn injury. The protection time for these clothing systems is estimated to be 1 to 5 minutes using the traditional TPP/RPP approach, which does not consider the discharge of thermal energy stored in the clothing system. By the stored-energy approach, however, the protection time for these selected fabric systems is lowed to 0.5 to 3 minutes.

The thermal stored energy accumulated in a fabric system during exposure could discharge naturally after the exposure and cause skin burn injuries. Therefore, considering the thermal stored energy predicts lower exposure time than TPP/RPP approach as the result of combination of transmitted and stored energy after the exposure. This physical phenomenon becomes extremely important when clothing is thick or multi-layered, and exposed to prolonged, relatively low levels of radiant heat. The amount of the energy stored in the system under these conditions is notable compared to the total exposure energy and it could cause skin damage after the exposure. The method and mechanism associated with thermal stored energy during the exposure and discharge after the exposure need to be further explored.

The impact of moisture on thermal protective performance when exposed to low radiant heat energy is complex, as it depends on the amount of moisture being absorbed, its distribution among the fabric layer system and the intensity of the exposure, etc. The results demonstrated the moisture residing in the clothing system increased the thermal protective performance significantly under these low radiant exposures.

Increasing the thickness of a fabric system by adding more layers improves the thermal protective performance, but also poses a physiological burden to wearers as these heavy, thick and bulky systems decreases the rate of heat and moisture exchange with the environment. Consequently these garments create tremendous heat stress and impede human body work performance and safety, especially in hot and humid environments. The structure of the fabric system is critical in determining the overall heat and moisture exchange.

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Authors' Note

Caution should be taken in drawing conclusions about safety benefits from the results. The data obtained in this research are from laboratory simulations under controlled laboratory exposure and specified conditions. These performance predictions do not represent clothing performance in actual field conditions where the nature of thermal exposure, clothing condition, human body response can be physically complicated and unqualified. We wish to emphasize that it is not our intention to recommend, exclude, or predict the suitability of any commercial product for a particular end-use.

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