A Study on Total Heat Loss of Clothing Materials for Firefighters' Protective Clothing

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Abstract

Clothing is often made of materials that impede the flow of heat and moisture from the skin to the environment. Consequently, people may suffer from heat stress or cold stress when wearing clothing in different environmental conditions. Therefore it is important to quantify the thermal resistance and evaporative resistance of clothing materials and to consider these properties when selecting materials for different clothing applications. The purpose of this study was to measure the resistance to dry heat transfer (conduction, convention, and radiation) and evaporative heat transfer provided by selected fabrics used in clothing worn by fire fighters or other rescue personnel. A comprehensive experimental work was conducted on a series of fabric samples to examine their thermal resistance, evaporative resistance, total heat loss, thermal protective performance and composite thickness. The thermal and evaporative resistance values were measured using a sweating guarded hot plate apparatus in an environmental chamber. These values were then used to determine the total heat loss that can be transferred through a fabric system in a specified environment.

Key words: Firefighters' Protective Clothing, Total Heat Loss, Thermal Protective Performance

1. Introduction

A firefighters' turnout coat is made of four basic components. Figure 1 shows these components from the exterior (top layer) to the interior (bottom layer). The first two are the outer shell and the moisture barrier. The thermal barrier, the third and fourth components are the thermal liner and face cloth combination, represented together in Figure 1. The face cloth is closest to the skin of the wearer and attached to the thermal liner. The thermal liner protects against heat penetration. The integrated moisture barrier component consists of the actual moisture barrier which is a plastic-like non-fabric product laminated to a fabric liner. The moisture barrier is designed to keep water out while allowing a limited amount of moisture vapor to exit. The exterior turnout coat component is the outer shell, which protects against flames and heat. The performance of a whole turnout coat depends on the choice of each of the four components (outer shell, moisture barrier, thermal liner, and face cloth). [1-2]

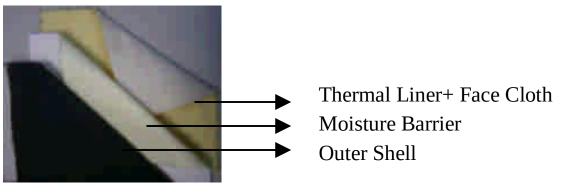


Fig.1. Components of Firefighters' Turnout Coat

The transfer of heat from the exterior of a material to the interior can be a significant factor in the level of protection or insulation provided by an assembly. Total heat energy from a fire can cause a worker's clothing to ignite or melt; it can cause the clothing to break open and subsequently cause severe burns to skin. The work of Stoll and Chianta in the 1960's helped to quantify the response of human skin and tissue to a source of heat energy. When human tissue is raised from the normal blood temperature of 36.5℃ to 44℃, skin burns begin to occur, at a rate that depends on the raised temperature level. For example, damage to skin at 50℃ is 100 times faster than that at 45℃, and at 72℃ total destruction of the epidermis occurs almost instantaneously. [3-6]The growing concern regarding health and safety of workers in various sectors of the industry has generated regulations and standards. The thermal protective performance (TPP) test method, which is an important test method for measuring thermal threshold index of firefighter's protective clothing.

The total heat loss (THL) requirement in NFPA 1971 provides a tool for examining the trade-off between thermal insulation (from heat) and the stress-related aspects of clothing materials. THL performance, or "breathability," as it's commonly known, is an important criterion to consider when selecting protective gear.

THL is used to measure how well garments allow body heat to escape. The test assesses the loss of heat, both by the evaporation of sweat and the conduction of heat through the garment layers. As clothing is made more insulating to high heat exposures, there is a trade-off with how well the heat build-up in the firefighter's body (that can lead to heat stress) is alleviated. Garments that include non-breathable moisture barriers or very heavy thermal barriers prevent or limit the transmission of sweat moisture, which carries much of the heat away from the body. If this heat is kept inside the ensemble, the firefighter's core temperature can rise to dangerous levels if other efforts are not undertaken (i.e. limiting time on scene). It's a well-known fact that there is only a 5º to 6ºC (9º to 10.8ºF) range in body core temperature between "normal" and being "at risk of death." However, with increases of only 1.5º to 2ºC (2.7º to 3.6ºF) you may make bad decisions that can affect your well being and that of other firefighters. [7] Even at this lower degree of increase, most individuals will experience fatigue, exhaustion, loss of efficiency, and possible nausea. In other protective gear such as emergency medical and search and rescue garments, increased moisture vapor breathability provides increased comfort and stamina with reduced heat stress. Thus the total heat loss test has been included in several NFPA standards to provide a balance between thermal insulation for protection and evaporative cooling insulation for stress reduction.

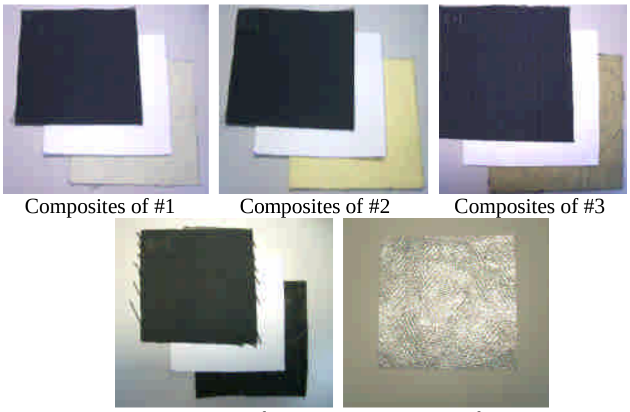
The THL test method, along with other minimum acceptable performance requirements, has now been added to five NFPA Clothing Standards over the past ten years. For structural fire fighting protective clothing, a new requirement 205 watts per square meter (W/m^2) was set for the new 2007 edition (replaces the old requirement of 130W/m^2). NFPA 1977-2005 Edition and NFPA 1999-2003 Edition for less insulation wildland fire fighting and Emergency Medical garments, which may be worn for extended periods of time, are subject to a requirement of 450W/m^2. In the new edition of NFPA 1951-2007 Edition, three different levels are set for Technical Utility (650 W/m^2), Rescue and Recovery (450 W/m^2), and CBRN (250 W/m^2). NFPA 1994 -2007 Edition for First Responder CBRN protective ensembles sets level of 200 W/m^2 for Class 3 garments and 450 W/m^2 for Class 4 garments. During this time, higher and higher minimum performance requirements have been established as the health and safety benefits, along with technical capabilities, have become better understood. [8-13]

2. Material

Table 1 Physical Characteristics of Five Garment Systems used for the Study

Sample Code and Description		Number of Layers	Composite Thickness (mm)	Composite Weight (g/m^2)
#1	A1-A2-A3	3	1.81	524
#2	A1-A2-B3	3	3.04	611
#3	B1-B2-C3	3	4.21	747
#4	C1-A2-D3	3	2.43	595
#5	---	1	1.11	534

Different types of firefighters' protective clothing were selected for study. Physical characteristics of five garment systems are given in Table 1. The #5 garment system is a Japanese turnout gear for firefighting. Three types of outer shell were used for the study, A1 and B1 are both Nomex III A, C1 is Oxided PA. Two types of moisture barriers were selected, A2 with PTFE membrane laminated on aramid nonwoven, B2 with PU-based moisture barrier laminated on aramid nonwoven. A3~D3, four different thermal barriers were selected, E89+(50% Nomex, 50% Viscose) , (Nomex/ Kevler batt)+ (50% Nomex, 50% VISCOSE) , (Oxided PA+ Kevlar batt)+ (VISCOSE), (Oxided PA spunlace)+ (VISCOSE) , respectively.



Composites of #1 Composites of #2 Composites of #3

Composites of #4 Composites of #5

Fig.2. Fabrics used in this study

3. Testing Method

3.1 Sweating Guarded Hot Plate

The Total Heat Loss test method, using the Sweating Guarded Hotplate, measures an ensemble composite's ability to reduce heat buildup. The insulation value and evaporative resistance value for the fabrics were measured using the total heat loss method specified in section 10 of ASTM F1868-2002, Standard Test Method for Thermal and Evaporative Resistance of Clothing Materials Using a Sweating Hot Plate, NFPA 1971-2007 Edition Standard for Protective Ensemble for Structural Fire Fighting.[14]

3.1.1 Apparatus and Test Conditions

A sweating guarded hot plate apparatus was used in an environment chamber. The guarded flat plate is composed of a test plate, guard section, and bottom plate, each electrically maintained at a constant temperature in the range of human skin temperature (33 to 36℃). The guard section is designed to prevent heat lateral loss of heat from the test plate. The bottom plate eliminates downward loss of heat from the test plate and guard section. A system for feeding water to the surface of the test plate and guard section is also needed for measuring evaporative resistance.

The test plate temperature was maintained at 35℃. For these measurements, the temperature and relative humidity of the air flowing over the test plate were 25℃ and 65% relative humidity respectively. Each test specimen was placed on the test plate with the side facing human body towards the test plate in the orientation that it would have in the finished garment from the skin side (plate) to the outside. When the conditions were within their tolerance limits and the systems had reached steady-state, the system was allowed to stay at equilibrium, which is defined in the standard as a rate of change of less than 3% per hour of the calculated thermal and apparent total evaporative resistance over a period not less than 30 minutes.

3.1.2 Calculations

3.1.2.1 Calculations for the Total Resistance to Dry and Evaporative Heat Transfer for a Fabric System, including the Surface Air Layer Resistance

The total resistance to dry heat transfer (R_{ct}) for a fabric system including the surface air layer resistance was calculated as Equation 1.

$$R_{ct} = \frac{(T_s - T_a)A}{H} \quad (1)$$

where:

R_{ct} = total dry heat transfer provided by the fabric system and air layer (℃・m^2/W)

A = area of the plate test section (m^2)

T_s = surface temperature of the plate (℃)

T_a = air temperature (℃)

H = power input (W)

Data from three replications of the dry thermal resistance tests were averaged to determine the mean value for each sample and for the bare plate.

The apparent total evaporative resistance (R_{et}^A) of the specimen provided by liquid barrier, fabric system and surface air layer was calculated as Equation 2.

$$R_{et}^{A} = \frac{(P_s - P_a)A}{H - \frac{(T_s - T_a)A}{R_{ct}}} \quad (2)$$

where:

Ret^A = apparent total evaporative resistance of the specimen and surface air layer (kPa・m^2/W)

P_s = water vapor pressure at the test plate surface (kPa)

P_a = water vapor pressure in the air flowing over the specimen (kPa)

Data from three replications of the apparent total evaporative resistance tests were averaged to determine the mean value for each fabric system (including the air layer and liquid barrier) and for the bare plate (the air layer and liquid barrier alone).

3.1.2.2 Calculations for the Average Intrinsic Resistance Values of the Fabric System Alone

The average intrinsic thermal resistance of the fabric system alone (R_{cf}) was determined by subtracting the average bare plate resistance (R_{cbp}) from the average total thermal resistance (R_{ct}) of the total fabric system tested as Equation 3.

$$R_{cf} = R_{ct} - R_{cbp} \quad (3)$$

The average apparent intrinsic evaporative resistance of the fabric system alone (R_{ef}^A) was determined by subtracting the average bare plate evaporative resistance (R_{ebp}) from the average apparent total evaporative resistance (R_{et}^A) of the total fabric system tested using Equation 4.

$$R_{ef}^{A} = R_{et}^{A} - R_{ebp} \quad (4)$$

3.1.2.3 Calculations of the Total Heat Loss for the Fabric System

The total heat loss of the fabric system was calculated as Equation 5.

$$Q_t = \frac{10^{\circ}C}{R_{cf} + .04} + \frac{3.57kPa}{R_{ef}^{A} + .0035} \quad (5)$$

where:

Q_t = total heat loss (W/m^2)

3.2 Thermal Protective Performance (TPP)

A thermal protective performance tester was used in this study for evaluating the thermal protective performance of the test materials. The test procedure used was in accordance with NFPA 1971-2007 Edition.

3.2.1 Apparatus and Test Conditions

The specimen mounted in a static horizontal position is placed a specified distance from a combined convective/radiant heat source and exposed until sufficient heat energy passes through the specimen to cause the equivalent of a second-degree burn injury in human tissue, or indicate a temperature rise of 24℃ in the sensor.

The equipment combines two gas burners and a bank of nine quartz radiant tubes calibrated to provide a 50% radiant energy and 50% convective energy. This equalized output is set to an exposure heat flux of 84±2 kW/m^2 (2.0±0.05 cal/cm^2/s).

The heat transfer may be compared with the times for the heat energy transferred through the specimen to cause a second-degree burn, the thermal threshold index (TTI), as based on human-tissue tolerance data. [9, 15]

3.2.2 Calculations of Thermal Threshold Index

The thermal threshold index analysis method shall be reported as TPP rating. The TPP rating is defined as the total exposure energy, which causes the turnout composite to transfer a sufficient amount of heat to cause a second-degree burn injury (blister), and was calculated as Equation 6.

$$TTI = F \times T \quad (6)$$

Where:

TTI = the thermal-protection index (kWs/m^2; cal/cm^2)

F = exposure energy heat flux (kW/m^2; cal/cm^2/s)

T = time to burn (s)

3.3 Fabric Thickness

The thickness of the component fabrics was measured according to ASTM Standard Method D1777-1996 for Measuring Thickness of Textile Materials. A presser foot at 4.14 kPa of pressure was used for all fabrics. The thickness values are reported in Table 1 and Table 3. [16]

3.4 Fabric Weight

The weight of the component fabrics was measured according to ASTM Standard Method D3776-1996 for Measuring Mass Per Unit Area of Fabric. The composite weight values are reported in Table 1. [17]

4. Results

4.1 NFPA Total Heat Loss Data

The intrinsic thermal resistance values, the apparent intrinsic evaporative resistance values, and the total heat loss values for the specimens are given in Table 2. Figure 3 showed the calculated results with use of Equation 3~5 for different garment systems, respectively.

Table 2 NFPA Total Heat Loss Data

Sample Code	Intrinsic		Total Heat Loss -Qt (W/m^2)
	Rcf (m^2・℃/W)	ARef (m^2・kPa/W)	
#1	0.084	0.0130	297.0
#2	0.130	0.0209	205.1
#3	0.188	0.0304	150.4
#4	0.139	0.0156	242.8
#5	0.042	0.0571	180.9

In Figure 3, it appears that garment systems #1~#2 and #4 which ensemble configurations involving moisture barrier A2, meet the NFPA 1971-2007 Edition requirement for THL of 205 W/m^2. The #3 garment with polyurethane-based moisture barriers analyzed have ensemble THL value in the 150 W/m^2 range.

According to NFPA 1971, a new requirement 205 watts per square meter (W/m^2) was set for the new 2007 Edition (replaces the old requirement of 130W/m^2), that is, the lower two garment systems #3 and #5 appear to have THL values ranging from about 150 to 180 W/m^2, a range in which do not meet the new 2007 NFPA requirement.

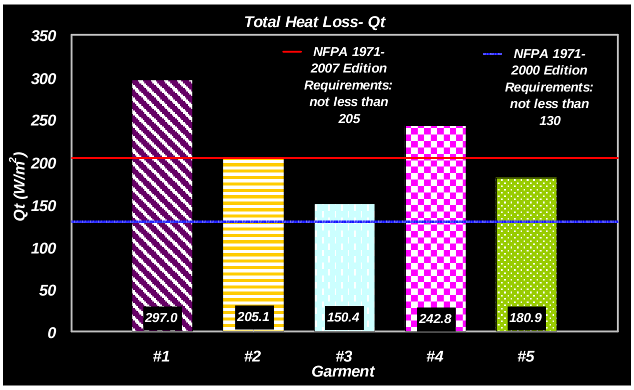


Fig.3. Total Heat Loss of the Five Different Garment Systems Measured by the Sweating Guarded Hot Plate

4.2 Thermal Protective Performance (TPP) Test Data

Figure 4. showed that calorimeter temperature response for the five garment systems. The TPP criteria curve for onset of second-degree burn is also presented.

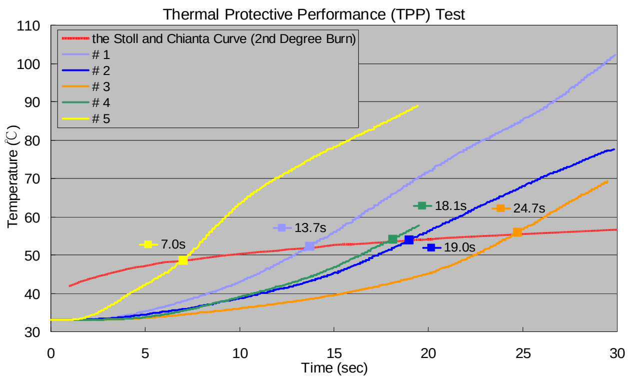


Fig.4. Stoll and Chianta Curve vs. The Sensor Response Curves of Different Garment Systems during the TPP Test

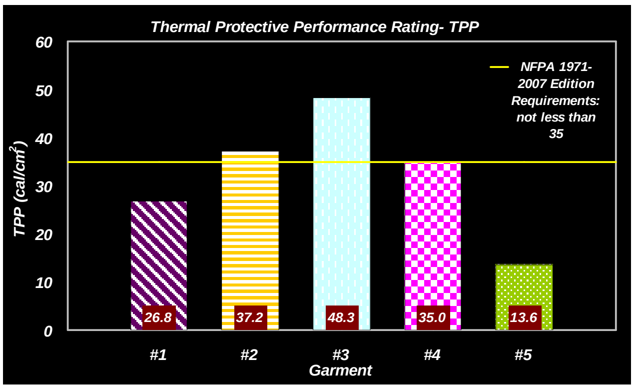


Fig.5.The TPP Rating of the Five Different Garment Systems Measured by the Thermal Protective Performance Tester

Results of thermal analysis by measuring TPP ratings of the five garment systems are shown in Figure 5. As can be seen from the chart, we find that results of measurements of single layer garment system #5 showed the lowest value. But the best thermal performance of all is exhibited by the #3, which is the thickest and the heaviest garment system.

According to the requirement of NFPA 1971-2007 Edition, a minimum of TPP rating 35kWs/m^2 was required for garment and glove composites used in structural fire fighting. The lower two garment systems #1 and #5 appear to have TPP rating values ranging from about 13 to 26 kWs/m^2, a range in which do not meet the NFPA requirement.

4.3 Correlation between THL and TPP

Total heat loss (THL) and Thermal Protective Performance (TPP) are two important values that, when taken together, produce a good predictive indication of the level of safety and performance provided by turnout ensembles.

The chart Figure 6 showed the THL values versus TPP values of the 5 firefighters' protective clothing. The different symbols depict the different garment systems used in this study. The chart presents the analyzed data and provides a clear picture of five different garment systems fall on the THL and TPP scale, relative to NFPA 1971 (2007 Edition) and NFPA 1971 (2000 Edition) minimum performance requirements.

With the #1~#4 data there is an opposite trend, i.e. the higher the thermal protective performance rating, the lesser will be the total heat loss value. As the chart shows, the #2 garment system and #4 garment system deliver better breathability (THL) and more insulation (TPP) than other 3 garment systems, that is the garment systems #2 and #4 which ensemble configurations involving moisture barrier A2 and thicker thermal barrier, meet the NFPA 1971-2007 Edition requirement for THL of 205 W/m^2 and TPP rating of 35. The garment system #3 appear to have THL ranging about 150 W/m^2 and TPP rating about 48, meet the 2000 NFPA minimum requirement for THL of 130 W/m^2 and TPP rating 35, however do not meet the new 2007 NFPA requirement for THL of 205 W/m^2.

We can now choose to optimize the selection of composites by balancing composite total heat loss values with thermal protective performance values while still meeting the minimum performance for both areas of performance.

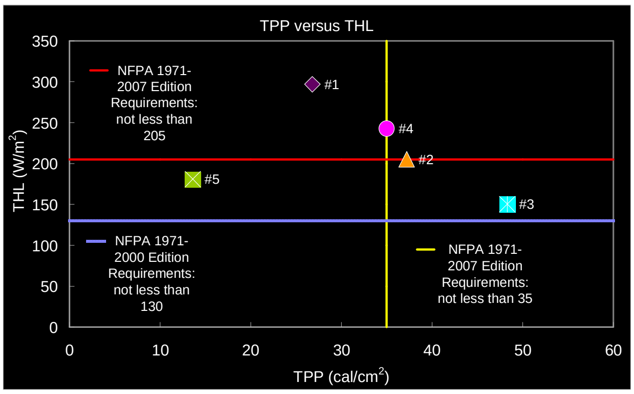


Fig.6. Correlation between THL and TPP

4.4 Material Thickness Results

Table 3 showed the composite thickness of the five Firefighter's Protective Clothing. As can be seen from Figure 5, the differences in the thickness of the outer shell and moisture barrier materials are not significantly different. Of three ensemble components, the thermal barrier has the greatest impact on composite thickness.

Table 3 Composite Thickness of the Five Firefighter's Protective Clothing

Sample Code and Description		Composite Thickness (mm)	Thickness (mm)		
			Outer Shell	Moisture Barrier	Thermal Barrier
#1	A1-A2-A3	1.81	0.57	0.45	0.83
#2	A1-A2-B3	3.04	0.57	0.45	2.00
#3	B1-B2-C3	4.21	0.66	0.47	3.01
#4	C1-A2-D3	2.43	0.70	0.45	1.39
#5	---	1.11	---	---	---

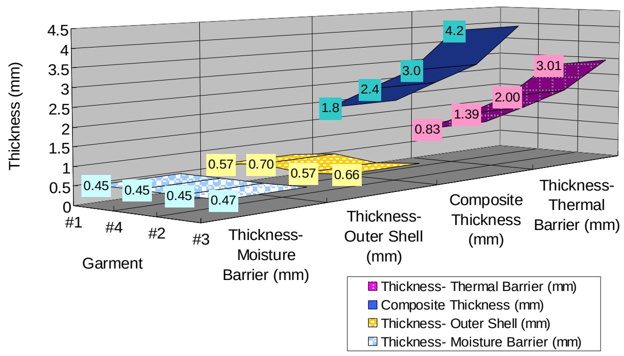


Fig.7.The Thickness of the Four Different Garment Systems

4.5 Correlation between THL, Composite Thickness and TPP

As can be seen from Figure 8, we find that thick and heavyweight fabrics exhibit high thermal protective performance, indicating that, as expected, the TPP rating of fabrics improves as their thickness or weight increases. Sample #3 performs better than other samples as regards the thermal barrier feature.

That is to say, as the material composite thickness increases, higher levels of thermal insulation (measured using TPP testing) are obtained. At the same time, thicker composites typically create more stress on the firefighter.

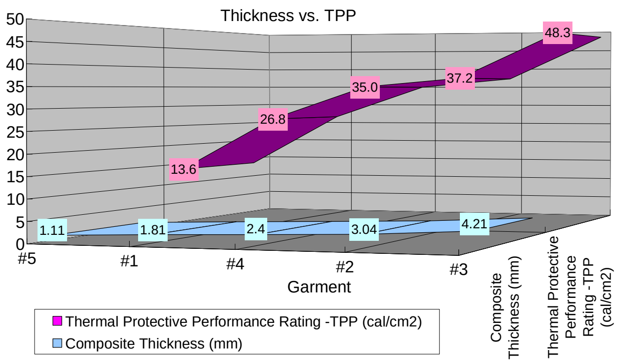


Fig.8. Correlation between Composite Thickness and TPP for Several Garment Systems

Of three ensemble components, the moisture barrier has the greatest impact on ensemble THL values, followed by the thermal liner and the outer shell.

In general, as the material composite thickness increases, higher levels of thermal insulation (measured using TPP testing) are obtained. At the same time, thicker composites typically create more stress on the firefighter.

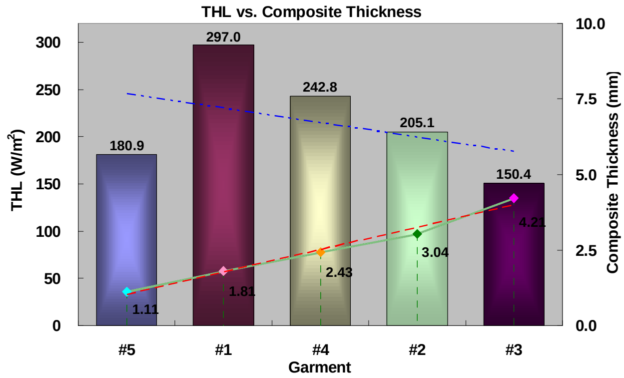


Fig.9. Correlation between Composite Thickness and THL

Moisture barriers have the greatest impact on THL, but THL is also affected by the choice outer shell and thermal barrier. Figure 9 showed the data trend for THL is that higher values are generated by thinner thermal barriers. And when comparing ensembles that incorporate the same moisture barrier selection, comparing #1~#2 and #4, the plot immediately depicts that the thermal barrier has significant impact in the overall balance of the ensemble THL-TPP performance. For TPP testing, thermal barriers usually have the greatest impact, but like THL, the TPP value for a composite is based on the contribution from each layer.

The garment composite breathability requirement has increased. A total heat loss (THL) value of 205 W/m^2 is now required compared to the former requirement of 130 W/m^2. This change eliminates some current moisture barrier and heavyweight composites as #3 garment systems, but affords a higher uniform level of stress reduction for structural fire fighting protective ensembles.

5. Conclusions

(1) The outer shell, thermal liner, and moisture barrier combination can dramatically affect the performance of firefighters' turnout gear.

(2) The TPP rating of fabrics improves as their thickness or weight increases.

(3) Of three ensemble components, the moisture barrier has the greatest impact on ensemble THL values, followed by the thermal liner and the outer shell.

(4) The choice of thermal barrier is the second most significant factor in determining ensemble THL results. The data trend for THL is that higher values are generated by thinner thermal barriers.

(5) With the advent of total heat loss testing, we can now choose to optimize the selection of their composites by balancing composite total heat loss values with thermal protective performance values (while both still meeting the minimum performance requirements).

(6) The garment composite breathability requirement has increased. A total heat loss (THL) value of 205 W/m^2 is now required compared to the former requirement of 130 W/m^2. This change eliminates some current moisture barrier and heavyweight composites, but affords a higher uniform level of stress reduction for structural fire fighting protective ensembles.

Acknowledgements

The authors would like to thank the Department of Industrial Technology, Ministry of Economic Affairs of the R.O.C. for the funding of this study through a four-year project on building up textile fundamental testing and research facilities.

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