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Study of the Effect of Material Assembly on the Moisture and Thermal Protective Performance of Firefighter Clothing

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Abstract
Heat protection and moisture comfort are important for firefighter protective clothing. In this study, the thermal protective performance (TPP) and water vapour transmission rate (WVTR) were measured for 16 assemblies. It was established that outer heat resistant fabric and the moisture barrier have significant effects on the TPP rating of assemblies. The moisture barrier also has a strong influence on the water vapour transmission rate of assemblies, and the WVTR of three-layer assemblies is much lower than that of single layer material. At the same time, the low moisture permeability of any layer will lead to a low WVTR of the turnout system. Considering thermal protection and moisture comfort, the optimal assembly of the overall materials is A1B1C2.

Key words: *firefighter protective clothing, thermal protective performance (TPP), water vapour transmission rate (WVTR), variance analysis.*

The growing concern regarding the health and safety of workers in industry has generated regulations and standards, as well as tremendous research and development in the area of firefighter protective clothing. Nowadays, typical firefighter clothing is a three-layer assembly consisting of an outer heat resistant fabric, a middle moisture barrier and an inner thermal liner. The outer shell fabric of firefighter protective clothing should not ignite, shrink, melt, or form brittle chars that may break open and expose the wearer. The moisture barrier should be waterproof and permeable to moisture. The thermal liner should have good heat insulation to prevent skin from burn injury. Therefore, not only excellent heat protection but also good moisture comfort is necessary when fire-fighters wear protective clothing during fire-fighting; they cannot work efficiently if they feel uncomfortable.

To this day, many researches have studied the effects of certain factors on the protective performance of firefighter clothing. Work by Young *et al* suggested that the thermal protective performance of fabrics was profoundly affected by the nature of the heat source and the intensity of the exposure [1]. Bengi suggested that washing caused a decrease in the TPP ratings of single-layer fabrics and an increase in the TPP ratings of multi-layer constructions [2]. Barker and Corinne demonstrated that moisture absorbed in the fabric plays a crucial and complicated role in the thermal protective performance during low-level radiant heat exposures [3 - 4].

However, so far, few researches have considered the material combination and effects of each layer on both the thermal protective performance and moisture comfort of firefighter protective clothing. Therefore, the objective of this study was to establish an optimal assembly of the overall materials in terms of their heat protection and moisture transmission. The TPP method and water vapour transmission test were applied in this study.

Experimental

Test samples

In this study, we selected the most appropriate fabric for firefighter protective clothing today; however, this was not a full-scale analysis. Four types of outer shell fabrics, two types of moisture barrier fabrics, which were coated with waterproof and vapour permeable PTFE, and two types of thermal liner were chosen for the experiment. Characteristics of the materials are listed in ***Table 1***.

In this study, 16 kinds of these material assemblies were generated by the enumeration method (***Table 2***).

Thermal protective performance

The most versatile laboratory instrument available for testing the thermal protection of fabrics is a TPP tester. A TPP tester - Custom Scientific Instrument 206 - was applied in this study. It is based on the NFPA1971 test standard [5]. It consists of two Meker burners and a bank of nine electrically heated quartz tubes controlled by a power-stat (***Figure 1***). The angle of the Meker burners to the horizontal was kept at 45° for this study so that the flame converged at a point immediately under the specimen. The heat sources are isolated from the test specimen by a water-cooled shutter to ensure accurate time exposures. A pneumatic shuttering mechanism activated by a digital timer allows the control of an exposure time of 0.2 s. This tester uses a combined flame and radiant source in time-controlled exposures to measure a thermal protective index.

Heat flux is measured by an copper calorimeter behind the test sample. The calorimeter face is blacked and mounted on an insulating board. A stainless steel plate provides light transverse friction and is intended to simulate semi-restrained con-

Table 1. *Characteristics of samples.*

Sample Code	Layer	Component	Structure	Area mass, g/m^2	Thickness, mm
A1	Outer shell	Aramid	twill	210	0.64
A2		Aramid	plain	150	0.46
A3		Fire resistant cotton	twill	225	0.67
A4		Aramid	twill	207	0.53
B1	Moisture barrier	PTFE Laminated on aramid fabric	coated	166	0.39
B2		PTFE Laminated on cotton fabric	coated	127	0.30
C1	Thermal liner	Polysulfonamide(PSA)	nonwoven	94	1.90
C2		Aramid	nonwoven	85	3.47

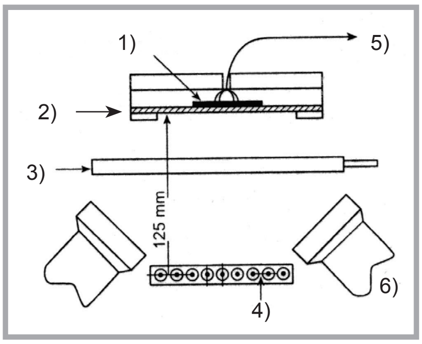

Figure 1. Scheme of CSI-206 TPP tester; 1 - Copper calorimeter, 2 - Test fabric, 3 - Water cooled shutter, 4 - Quartz tube bank, 5 - Recorder, 6 - Meker burner.

ditions existent in many clothing assemblies. The TPP tester is adjusted to transfer the heat output desired, as indicated by the reading on the copper calorimeter. The balance of radiant to convective heat is determined using a Hy-Cal radiometer. The calorimeter sensor is connected to a data acquisition system which provides a continuous record of the rate of temperature rise of the sensor. The temperature rise of the calibrated copper calorimeter is recorded on a high speed strip chart recorder with a resolution of 0.1 s. The rate of temperature rise versus the time trace is used in conjunction with calorimeter constants to calculate the heat flux received. This method uses Stoll data to translate the heat flux measurement into a time of protection [6].

The TPP rating is defined as the total exposure energy that causes the test fabric to transfer a sufficient amount of heat to cause a 2nd degree burn injury, which is calculated as follows:

$$\text{TPP rating} = F \times T \qquad (1)$$

where

F - exposure energy heat flux in w·cm^{-2}
T - time to burn in s.

The larger the TPP rating, the better the thermal protective performance of the fabric is. The sample was 15 cm ×15 cm, and the exposed area 100 cm^2. At least three samples of every assembly type were tested. Prior to testing, all samples were conditioned for at least 24 h at 65% RH and 21 °C.

Moisture transmission test

Moisture transmission was measured following a standard test procedure, as described in ASTM E96-2005 Upright cup (procedure A) [7]. It was used to measure the rate of water vapour transmission, perpendicular to the controlled atmosphere, through a known area of the fabric. In this method, as shown in ***Figure 2***, the sample covered a cup with desiccant, which was then placed in a controlled environment of 38 ± 1 °C and 90 ± 2% RH. The amount of moisture gained through the fabric was determined over a period of time and used to calculate the water vapour transmission rate in grams per hour and per square meter by the following equation:

$$WVTR = G/tA \qquad (2)$$

where

$WVTR$ - water vapour transmission rate in g·m^{-2}·h^{-1}
G - weight change of cup with fabric sample in g
A - area of test cup mouth in m^2
t - time in h.

The larger the $WVTR$, the better the moisture permeability of the fabric is.

Results and discussion

Effects of each layer on the thermal protective performance

A total exposure energy of 8.4 ± 0.4 W·cm^{-2} was chosen to simulate industrial or military flash fire conditions that are similar to emergencies encountered by fire fighters. In this study, the copper calorimeter was put in direct contact with the back surface of the fabrics. ***Figure 3*** shows calorimetric traces of the assemblies (No 1, No 5, No 9, No 13), which are identical with the exception of the outer shell fabrics. The temperature rise curves show that the heat transfer properties of the assemblies are different. It can be observed that the slope of No 9 curve is the steepest, whereas that of No1 is flattest, which means that the rate of temperature rise for No 9 was the most rapid, whereas that for No 1 was the slowest. Thus, the thermal protection performance of No 9 (FR cotton) is the poorest, whereas that of No 1 (aramid fibre) is the best. The cause of this may mainly be the fibre type. The thermal resistance of FR cotton fibre is inferior to that of aramid fibre. At the same time, the outer shell fabrics of No 1 and No 5 were made of the same fibre, but the thermal protection performance of No 1 was a little superior to that of No 5, which was probably mainly due to the thickness and weight of the outer shell fabrics. For the same fibre type, heavier or thicker fabric leads to a higher TPP rating.

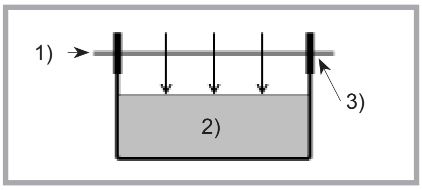

Figure 2. Scheme of ASTM E96; 1 - fabric sample, 2 - desiccant, 3 - sealant.

Results of the TPP rating are listed in ***Table 2***. It can be clearly observed that the different material assemblies have a different TPP rating. The TPP rating of No 1 is the highest.

According to the value of the range, which reflects the effect of each layer, the priority order of the three layers was B > A > C (***Table 2***); that is, the most important layers which influence the TPP ratings are the moisture barrier and outer

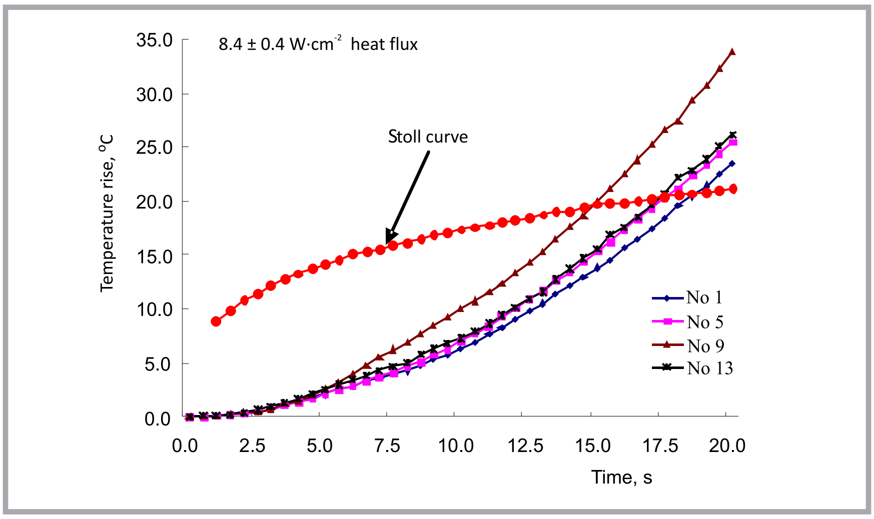

Figure 3. Temperature rise versus time of three-layer assemblies.

Table 2. Results of TPP rating.

Code	Outer shell	Moisture barrier	Thermal liner	TPP, W·cm^{-2}·s
No 1	A1	B1	C2	156.9
No 2	A1	B2	C1	136.4
No 3	A1	B1	C1	154.0
No 4	A1	B2	C2	133.5
No 5	A2	B1	C2	148.5
No 6	A2	B2	C1	129.3
No 7	A2	B1	C1	145.6
No 8	A2	B2	C2	123.0
No 9	A3	B1	C2	125.9
No 10	A3	B2	C1	117.2
No 11	A3	B1	C1	125.1
No 12	A3	B2	C2	117.2
No 13	A4	B1	C2	145.6
No 14	A4	B2	C1	136.8
No 15	A4	B1	C1	146.4
No 16	A4	B2	C2	146.9
K_1	580.7	1148.1	1097.5	K_1, K_2, K_3, and K_4 are the sum of TPP for each layer of the different materials, respectively.
K_2	546.4	1040.1	1090.8	
K_3	485.3			
K_4	575.7			
R	95.4	107.9	6.7	R is the range of each factor.

Table 5. Analysis of Variances for WVTR.

Factor	R	SS	DF	MS	F	Sig.
A	32	132.2	3	44.1	0.83	
B	152	1446.9	1	1446.9	27.1	**
C	30	55.7	1	55.7	1.05	
Error		532.8	10	53.3		

shell. The thermal liner seems to be effective but is of less importance. For each layer, the optimal material is determined by K_1, K_2, K_3, and K_4. The greater the K value, the better thermal protective performance is. From this we can state that the priority order of the outer shell is A1 > A4 > A2 > A3, that of the moisture barrier B1>B2, and for the thermal liner it is C2 > C1. Thus, the best combination for the thermal protective performance is A1B1C2 (No 1). This result is consistent with the TPP rating.

In order to discuss the significance of each layer for thermal protective clothing, the F values of each layer are calculated by an analysis of variances (***Table 3***). Results show that the effects of different outer shells and moisture barriers for TPP are statistically significant ($F_A = 16.11 > F_{0.01(3,10)} = 6.55$, $F_B = 24.43 > F_{0.01(1,10)} = 10.04$). However, the effect of the thermal liner is not significant ($F_C = 0.09 < F_{0.10(1,10)} = 3.29$), meaning that the significant layers which influence heat protection are the outer shell fabric and moisture barrier. These can be explained by the fact that the outer shell fabric and moisture barrier are the outermost layers of the assembly and come into contact with fire easily. However, the thermal liner is in an inner layer of the assembly, which is far away from the flame.

Table 3. *Analysis of Variances for the TPP rating; ** Difference is significant at a level of 0.01.*

Factor	SS	DF	MS	F	Sig.
A	83.32	3	27.44	16.11	**
B	41.60	1	41.60	24.43	**
C	0.16	1	0.16	0.09	
Error	17.03	10	1.703		

Effects of each layer on moisture transmission

Besides excellent heat protection, better moisture permeability is necessary when a firefighter sweats during fire fighting. To study the effect of materials on moisture transfer, the *WVTR* of single layer and three-layer materials, as mentioned before, were tested. ***Figure 4*** shows the results of the water vapour transmission rate of single-layer materials. It can be observed that the *WVTR* of the single layer material ranges between 181 and 246 g·m^{-2}·h^{-1}. The best water vapour transmission rate of all the single-layer materials is A2, which may be due to its thinness and plain structure, as moisture diffuses easily with thin and porous fabric.

WVTR results of three-layer assemblies are shown in ***Figure 5***. To investigate the effect of each layer on moisture transfer, an analysis of variance was also conducted. From the analysis of variances for *WVTR*, it can be stated that the effect of the moisture barrier is significant ($F_B = 27.15 > F_{0.01(1,10)} = 10.04$) (***Table 4***). However, the effects of the outer shell and thermal liner are not significant. The moisture barrier, therefore, does play a significant role in determining the moisture transfer. Hence, the best moisture barrier is B1.

Moreover, the *WVTR* of three-layer assemblies is much lower than that of single layer material (***Figure 4, Figure 5***). This can be partly explained by the fact that the thickness of a three-layer assembly is greater than that of a single layer. The water vapour transmission rate decreases with the number of layers, and also when the thickness of the assembly increases. At the same time, each layer is relatively important for moisture transmission. The low moisture permeability of any layer will lead to a low *WVTR* of the turnout system. For instance, the ***WVTR*** of the B2 moisture barrier is the poorest of all. As a result, the *WVTR* of assemblies containing B2 are lower than that of assemblies without B2.

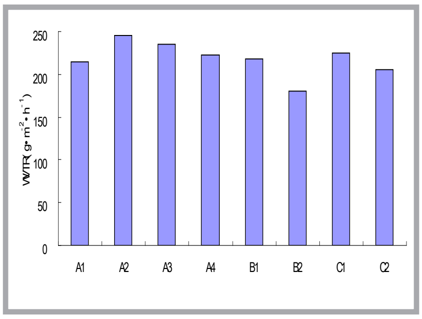

Figure 4. *WVTR results of single-layer material.*

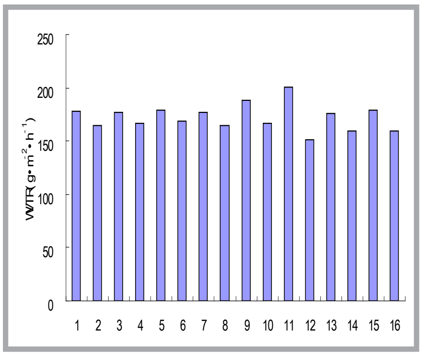

Figure 5. *WVTR results of a three-layer assembly.*

Conclusions

This study evaluated the heat protection and moisture transfer of firefighter protective clothing. The thermal protection performance and water vapour transmission rate were measured for 16 different combinations of the materials. It was found that, by analysis of variances, the outer shell and moisture barrier have significant effects on the thermal protective performance. The best material of the three layers is A1, B1, and C2, respectively.

The *WVTR* of three-layer assemblies is much lower than that of single-layer material, and the moisture barrier has a strong effect on the moisture permeability of firefighter's protective clothing. The water vapour transmission rate decreases with the number of layers, and also when the thickness of the assembly increases. At the same time, each layer is relatively important for moisture transmission. The low moisture permeability of any layer will lead to a low *WVTR* of the turnout system.

Considering heat protection and moisture comfort, the optimal material assembly is A1B1C2. The knowledge gained from this research can be useful in designing firefighter protective clothing with optimum protection and comfort.

Acknowledgment

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