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Thermal Analysis and Performance Properties of Thermal Protective Clothing

Abstract
In this study, a thermal protective performance (TPP) test was applied for thermal analysis. The thermal analysis by the TPP test was carried out on the single layer-fabrics and their assemblies in two- and three-layerconstructions. The thermal protective performance ratings of these constructions and each single outer layer fabrics were determined. Thickness and area mass seem to influence the TPP ratings of single-layer fabrics. Four types of outer layer fabrics and one type of third-layer fabric were also tested in the Du Pont Engineering Fibres Laboratory. The results obtained in our laboratory were compared with Du Pont's test results. Also, each fabric was washed 1, 3, 5, and 10 times. TPP ratings, air permeability, area masses and tear strengths of fabrics were measured before and after certain washing cycles. Dimensional changes at the end of washing were also determined. The highest TPP ratings were obtained from the three-layer (outer layer + thermal barrier + inner layer) structures. According to the results, fabrics shrink, air permeability values and tear strengths were decreased, and the area mass of test samples increased with the increase in the number of washing cycles. Washings cause a decrease in TPP ratings of single-layer fabrics and an increase in TPP ratings of multi-layer constructions.

Key words: *Thermal protective performance (TPP), thermal protective clothing, washing, area mass, tear strength, air permeability.*

Introduction

Modern technological developments have brought with them a vast increase in the kinds of hazard to which workers are exposed. Most of these hazards are encountered in work-places. Work-place hazards can be grouped in chemical, mechanical, radiation, biological, and thermal hazards [1,2].

Personal protective equipment, which includes personal protective clothing and gear such as respirators, face masks, and other controls, forms a barrier between the person and the hazardous environment. The dangers are frequently so specialized that no single type of clothing will be adequate for work outside the normal routine. Protective clothing made from woven, knitted, and nonwoven fabrics have been designed to suit specific requirements, and performance-evaluation techniques to simulate the workwear conditions have been developed [1-3].

To overcome thermal hazards, heat and flame resistant fibers are used to produce thermal protective clothing. Thermal protective clothing should not ignite, they should remain intact, not shrink, melt, or form brittle chars that may break open and expose the wearer; and they should provide as much insulation against heat as is consistent with not diminishing the wearer's ability to perform a task. In Table1, there are some occupations in which the hazards from heat and flame are such an integral part of the job that the worker needs to wear protective clothing more or less continuously [1-3].

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 ^{o}C to 44 ^{o}C, skin burns begin to occur, at a rate that depends on the raised temperature level. For example, at 50 ^{o}C, damage to the skin is 100 times faster than at 45 ^{o}C, and at 72^{o}C total destruction of the epidermis occurs almost instantaneously [4-6].

The growing concern regarding health and safety of workers in various sectors of the industry has generated regulations and standards, environmental and engineering controls, as well as tremendous research and development in the area of personal protective equipment. There are a number of different tests used for evaluating thermal characteristics of protective clothing, such as ease-of-ignition tests, flammability tests, heat-release-measurement tests, extinguishability tests, tests for measuring thermal insulative properties of fabrics and thermo-person full scale garment burns [2, 4].

In this study, we aimed to select the most appropriate fabric or fabric assembly for usein producing thermal protective clothing, although this was not a full-scale analysis. To achieve this aim, a thermal analysis of thermal protective fabrics and assemblies was made. For this analysis, we used the thermal protective performance (TPP) test method, which is an important test method for measuring thermal protective fabric's insulative properties. We constructed a test apparatus at our department based on the above-mentioned test method . Secondly, to see how the fabrics change during use, a series of washings was carried out. After the washings, the air permeability, area masses, dimensional changes, tear strengths and TPP ratings of the fabrics were measured.

Table 1. *Hazardous Occupations Requiring Protection against Flame and Heat.*

Industry	Flame	Thermal Contact	Radiant Heat
Foundry (Steel and glass manufacturing, metal casting, forging)	*	**	**
Engineering (Welding, cutting, boiler work)	*	**	*
Oil, gas, and chemicals	*	-	-
Aviation and space	*	-	-
Military	**	*	*
Firefighters	**	*	*

** Major hazard; * Subsidiary hazard; - Minor/no hazard,

Materials and methods

Materials

The compositions of fabrics were as follows:

- 60% Nomex Delta A/40% para-aramid (Fabric No. 1),
- 40% PBI/60% para-aramid (Fabric No. 2),
- Nomex III (+1% steel fibre) (Fabric No. 3),
- Nomex Delta T/2% antistatic fibre (P140) (Fabric No. 4), and
- 50% Nomex/50% FR-viscose (Fabric No. 5).

The first four fabrics (1, 2, 3 and 4) are outer shell fabrics, and the fifth fabric (5) is an inner layer fabric for thermal protective clothing. An assembly of fabrics was also used; is aramid/FR-viscose fabric (35/65) quilted on 100% aramid felt (Fabric No.6); it is thus used as a thermal barrier + inner liner. The properties of the fabrics are listed in Table 2. Thermal analysis by the TPP test was carried out for the single layer fabrics, their two-layer assemblies with Fabric 5, and te three-layer assemblies with Fabric 6.

Table 2. Fabrics used in this study.

Fabric	Area mass, g/m²	Fabric thickness, mm	Type of weave	Setting, cm^{-1}		Linear Density	
				Warp	Weft	Warp	Weft
1	229.88	0.54	Plain	22.0	21.0	Nm 40/2 (25.0 tex × 2)	Nm 40/2 (25.0 tex × 2)
2	206.60	0.58	Plain	21.5	18.0	Nm 40/2 (25.0 tex × 2)	Nm 40/2 (25.0 tex × 2)
3	265.48	0.53	Twill	29.0	21.0	Nm 40/2 (25.0 tex × 2)	Nm 56/2 (17.9 tex × 2)
4	195.30	0.48	Twill	28.0	26.0	Nm 56/2 (17.9 tex × 2)	Nm 56/2 (17.9 tex × 2)
5	129.58	0.31	Plain	38.0	23.5	Nm 50 (20.0 tex)	Nm 50 (20.0 tex)
6	331.13	3.79	Plain	34.0	24.5	Nm 52 (19.3 tex)	Nm 52 (19.3 tex)

Thermal Protective Performance Test Method

The thermal protective performance (TPP) rating of a fabric is the amount of energy in cal cm^{-2} which must be applied to the fabric until it is estimated that second-degree burns of the skin behind the fabric would occur, using the Stoll criterion. As the heat flux of 2 cal cm^{-2} s^{-1} (84 kW m^{-2}) is used, the TPP rating is simply found by multiplying the time to exceed the Stoll second-degree burn criterion by two. The larger this number, the greater the protection factor of the fabric system [4, 7, 10].

Thermal protective performance test methods use data from the work of Stoll & Chianta to estimate the time it takes for second-degree burn damage to begin for a given exposure. This data is converted to the total amounts of energy that must be absorbed by the skin, and to skin temperature rises, to cause second-degree burns for a given amount of exposure to heat and length of exposure. The temperature rise recorded can hence be compared with this criterion to estimate the time required to produce a second-degree burn [4, 5].

The test apparatus constructed for this study is based on the NFPA test method 1971 (Figure 1) [7]. This equipment combines two burners and a bank of nine quartz tubes calibrated to provide a 50% radiative and 50% convective heat flux at a total flux of 84±5 kW m^{-2} (2±0.1 cal cm^{-2} s^{-1}). A shutter protects the fabric sample from high heat flux before and after the test run. The specimens measure 150 mm by 150 mm and are placed horizontally on the heat sources, between an upper and lower mounting plate. The heat sensor is mounted in direct contact with the back surface of the fabric that would normally rest against the skin. In standard NFPA 1971, there is a spacer between the heat sensor and the back surface of the fabric in the case of single-layer fabrics. However, we did not use this, because it was found to increase all the values recorded and to distort the results with some materials more than others [8]. The heat sensor consists of a copper calorimeter and an insulating board in which the calorimeter is mounted. The copper calorimeter is blackened and has a 40 mm diameter with a thickness of 1.6 mm; three thermocouples are secured in the disk, positioned at 120° intervals. [4,7,9,10].

The TPP tests for all these specimens were repeated three times. The fabric layers were sewn together so that one just touched another. Before beginning the tests, the sensor was cooled to approximately body temperature, below 38 °C. After the beginning of the exposure, the temperature was recorded every three seconds. The temperature rise was calculated by subtracting the starting temperature from the recorded temperatures, and temperature rise versus time curves were plotted. The curve recorded in terms of the rises in temperature was compared with Stoll's second-degree burn criteria, in order to calculate the protection time. The TPP ratings were determined by multiplying the protection time by the heat flux density of 2 cal cm^{-2} s^{-1}.

We sent samples of four types of outer-layer fabrics (1, 2, 3 and 4) and one type of third-layer assembly (4 + 6) to the Du Pont Engineering Fibres Laboratory in Meyrin, Switzerland to be tested there. Then we compared the results of the Du Pont tests with the results from our apparatus. A spacer of 6 mm was used in the Du Pont tests for single-layer fabrics. The effects of laundering on TPP rat-

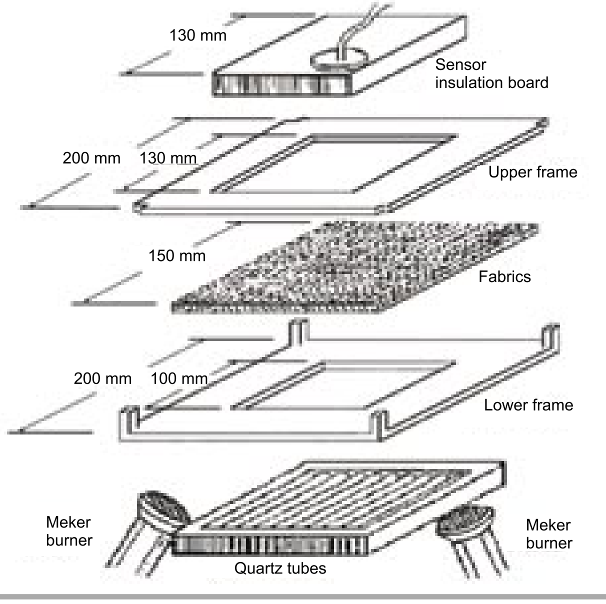

Figure 1. Plan of the NFPA 1971-1991 test apparatus.

ing, area mass, air permeability and tear strength were examined. Before washing, and after 1 cycle, 3, 5, and 10 cycles, these properties of each specimen were measured

Measurements of Performance Properties

Fabrics were washed for a total of 10 cycles.. Dimensional changes by washing were also determined. Washing was performed in an automatic washing machine at 40 °C and using a program of approximately 1 hour length. It was recommended that fabrics should be washed in warm water (not higher than 60 °C) and for a maximum of 1 hour length; so this washing condition was selected. The amount of detergent used is 5 g/l and the liquor ratio is 1:5 [11-14].

Measurements of dimensional changes, air permeability and tear strength of fabrics were made according to AATCC 135, DIN 53 887 and ASTM 2261 respectively.

Results and discussion

Results of the Thermal Protective Performance Test

TPP Ratings of Single- and Multi-Layer Fabrics

Results of thermal analysis by measuring TPP ratings of fabrics and assemblies are shown in Table 3. The data are presented in tolerance time and in TPP ratings. The maximum and minimum of TPP ratings from measurements are also represented to give an idea about the accuracy of our apparatus.

Generally, results of measurements of single layer fabrics show close values. But the best performance of all is exhibited by the fabric 2. It is the thickest and the only fabric containing PBI fibers, although the heaviest fabric is fabric 3, which has the second highest TPP rating. One of the reasons of lower TPP rating of this fabric may be the construction of the fabric, because it has a compact structure (twill) and this may increase heat transfer by conduction. Fabric 1 has the same weave fabric 2 and is heavier than this fabric but has a lower TPP rating. The cause of this may be its thickness and its fiber type is different and the fiber type used (is thinner than fabric 2).

From this table, it is obvious that adding a layer, even with a low area mass and low thickness to the outer layer fabric is very useful for thermal performance. As the maximum TPP rating in single layer samples is 11.5, the maximum value for two layer fabrics increases to 15.2 as in table. So this is an indicator of why protective clothing must be produced from multi-layer fabrics and not with single fabrics of high area mass; because air trapped in the fabric layers is a good insulator.

In the test, the three-layer assemblies have greater thickness; and are heavier and bulky. Therefore it permits to obtain higher TPP ratings. The maximum TPP value is observed from again PBI/p-aramid sample and is 34.8 cal cm^{-2}. In NFPA 1971 standard, the TPP rating required for a multi-layer fabric consisting of an outer layer, a thermal layer and a moisture layer is 35.0 cal cm^{-2}. Consequently, it seems that the TPP rating of 34.8 cal cm^{-2} without moisture barrier is almost sufficient for insulation [7].

Burning Behaviors of Fabrics

Among fabrics, PBI /p-aramid 40/60 suffers the least hazard at the end of the TPP test. It does not ignite but becomes black in color. Generally char and ash do not form and the fabric is flexible at the end of the tests. Even if the fabric is exposed to flame and heat for a long time, it does not ignite. The fabric glows with flame but there is no afterglow when flame is removed. When glowing occurs in the test, the fabric forms a brittle char. However in the case of TPP tests of single layer fabrics there is usually no glowing. The fabric glows with odor and colorless smoke [18].

The black color of Nomex Delta A /p-aramid 60/40 fabrics becomes yellowy at exposure area. The fabric does not shrink by heat. There is a char after exposure. If the flame and heat are applied for a long time, the fabric forms brittle chars. There is white smoke with a bad odor for all aramid fabrics. The reason for this is thought as the nitrogen in their structures.

The exposure areas of fabrics are also yellowy. This may be due to the degradation of pigments of dyestuffs with elevated temperatures. Of all, the highest shrinkage by flame and heat is seen in Nomex III. After the tests, the fabric forms bright and thick chars. The char is brittle, but due to its thickness it does not break easily. In the tests, there is a liquid on the back surface of the fabric when exposure time is long.

Nomex Delta T /P140 forms char quickly. Generally after almost all tests a brittle char is formed. There is shrinkage by heat and flame and there is no color change.

Comparison with Du Pont Laboratory

The ratings obtained in Du Pont laboratory are higher than those of our laboratory for single layer fabrics (Table 4). This is due to the spacer (6mm) used in Du Pont test for single layer fabrics. The spacer provides insulation between fabric and heat sensor. Spacer was not used in our measurements; thus the calorimeter was in direct contact with the fabric. Direct contact increases the amount of heat transferred from fabric to the calorimeter. This is the reason for TPP rating differences between the two test results for single layer fabrics. For assembly the difference is not as big as the difference between the results of the single layer fabrics; because spacer is not used for assemblies.

TPP test method consists of some parameters that cannot be controlled. The test results may vary slightly between laboratories. One reason for this may be the fact that every flame or fire is different [17].

Effects of Washing on Properties of Thermal Protective Clothing

While washing removes contamination, it can also damage clothing materials in time. Detergents and specialized cleaning products may also cause some degrada-

Table 3. *TPP Ratings of Fabrics and Assemblies.*

	Fabrics	Tolerance Time, s	TPP, cal/cm^2	Max. TPP	Min. TPP
Single Layer	1	5.3	10.5	12.0	8.8
	2	5.7	11.5	13.0	8.9
	3	5.4	10.8	11.6	10.0
	4	3.5	7.1	7.6	6.8
Two Layers	1 + 5	7.1	14.2	15.0	13.0
	2 + 5	7.6	15.2	15.4	15.0
	3 + 5	7.3	14.6	17.0	12.0
	4 + 5	7.0	14.0	16.3	11.7
Three Layers	1 + 6	15.5	30.9	32.8	29.0
	2 + 6	17.4	34.8	35.4	34.0
	3 + 6	12.9	25.7	26.6	25.0
	4 + 6	14.4	28.7	31.2	27.2

Table 4. TPP Ratings from Our Measurements and Du Pont Laboratory Measurements.

Type of fabric	Number of layer	TPP ratings, cal/cm^2	
		Our Results	Du Pont Results5
Single Layer Fabrics	1	10.5	12.9
	2	11.5	13.1
	3	10.8	15.3
	4	7.1	12.4
Assembly	4 + 6	28.7	27.4

tion of fabric properties and it may cause a decrease in the performance properties of clothing. These effects become more pronounced as the number of washing increases. In the following, we give the results of the effects of washing on the fabrics' properties. [15].

Effects of Washing on TPP Rating, Air Permeability, Area Mass and Dimensional Changes after Washing

Variations in the properties of fabrics caused by washing are shown in Tables 5, 6, 7, 8, 9, 10. It can be seen from the tables that the air permeability values change inversely with the number of washing cycles, while the area masses of fabrics were increased with the increase in the number of washing cycles. Dimensional changes took the form of shrinkage. According to NFPA 1971, dimensional changes in warp and weft directions must be below 5%. In this study, the maximum value observed in the warp direction is 1.53% in PBI/p-aramid fabric, and in the weft direction is 1.33% in the Nomex Delta A/p-aramid. These values are somewhat lower than 5% [7]. All of these facts show that fabric densities have increased with washing. However after 10 washings, the changes in air permeability values were rather greater than the changes in area mass and dimensional changes. This shows that another reason of the change in air permeability values could be the fluffing of the fabrics.

Table 5. *Air permeability values before and after washing cycles.*

Fabrics	Air permeability values, l m^{-2} s^{-1}				
	Before washing	1st washing	3rd washing	5th washing	10th washing
1	268.5	219.0	191.6	194.4	169.7
2	208.0	175.0	168.3	149.8	135.9
3	77.7	63.9	63.8	63.7	63.7
4	159.9	135.2	133.1	127.4	125.6
5	377.3	361.0	347.8	336.7	330.8
6	364.0	298.8	302.2	293.6	278.4

Table 6. *Area mass of fabrics before and after washing cycles.*

Fabrics	Air permeability values, l m^{-2} s^{-1}				
	Before washing	1st washing	3rd washing	5th washing	10th washing
1	229.88	233.08	232.40	234.75	235.18
2	206.60	208.22	207.23	210.98	210.33
3	265.48	270.08	271.08	272.10	272.38
4	195.30	197.50	197.18	198.55	199.95
5	129.58	128.55	129.95	131.20	132.88
6	331.13	333.73	332.85	353.90	368.33

Table 7. *Dimensional Changes of Fabrics after Washing Cycles.*

Fabrics	Dimensional changes, %							
	1st washing		3rd washing		5th washing		10th washing	
	warp	weft	warp	weft	warp	weft	warp	weft
1	-0.80	-0.73	-1.00	-0.73	-1.07	-0.13	-1.33	-1.00
2	-0.33	-0.60	-0.67	-1.07	-0.87	-1.27	-0.93	-1.53
3	-0.46	-0.37	-0.67	-0.37	-0.67	-0.66	-0.87	-0.66
4	-0.26	-0.27	-0.33	-0.33	-0.60	-0.40	-0.73	-0.67
5	-0.27	-0.46	-0.20	+0.20	-0.13	+0.13	-0.20	-0.17
6	-0.26	-0.33	-0.37	-0.37	-0.13	-0.40	-0.13	-0.43

Effects of Washing on TPP Rating, Air Permeability, Area Mass and Dimensional Changes after Washing

Variations in the properties of fabrics by washing are shown in Tables 5, 6, 7, 8, 9, 10. It can be seen from tables that air permeability values change inversely with washing cycles while area masses of fabrics were increased with increasing number of washing cycles. Dimensional changes were in form of shrinkage. According to NFPA 1971, dimensional changes in warp and weft directions must be below 5%. In this study, maximum value observed in warp direction is 1.53% in PBI/p-aramid fabric and in weft direction is 1.33% in Nomex Delta A/p-aramid. These values are somewhat lower than 5% [7]. All of these show that fabric densities have increased with washing. However after 10 washings, the changes in air permeability values were rather more than the changes in area mass and dimensional changes. It shows that the another reason of the change in air permeability values should be the fluffing of the fabrics.

The TPP ratings of single-layer fabrics showed a small amount of decrease, but that of the assemblies increased after various numbers of cycles. The results are related to the changes in air permeability, area mass and dimensional changes. Single-layer fabrics exhibit a decrease in TPP because fluffing, shrinkage and higher area mass in the fabrics arise; and so, the heat transfer by conduction may increase a little. On the contrary, the TPP ratings of the assemblies increase. The cause may be the layered construction of these samples. Fluffing may increase the air entrapped in the fabric layers and the overall thickness. Therefore, the TPP of assemblies increase while the TPP of single fabrics decrease. These results resemble the measurements of Stull's study. Stull et al. (1996) recorded rises in TPP ratings after 25 washing cycles. They explain this rise as fluffing and increased thickness, and thus the increased insulation of the fabric after washing cycles [7].

Tables 8, 9 and 10 show data obtained on the single-outer layer fabrics, two layer fabrics and three layer fabrics respectively.

Effects of Washing on Tear Strength

Fabrics which consist of para-aramid fibres have a rather higher tear strength than other fabrics. As seen in Table 11, the tear strengths of fabrics is decreased by washing. These results exhibit similarities with the observations in Stull's

Table 8. *TPP test results of single layer fabrics.*

Fabric	Tolerance time (TT), s	TPP, cal/cm2	TT, s	TPP, cal/cm2	TT, s	TPP, cal/cm2	TT, s	TPP, cal/cm2	TT, s	TPP, cal/cm2
	Before washing		1st washing		3rd washing		5th washing		10th washing	
1	5.3	10.5	3.5	7.0	4.0	7.9	4.4	8.7	4.5	9.0
2	5.7	11.5	6.2	12.4	4.9	9.9	4.8	9.7	5.0	10.0
3	5.4	10.8	3.8	7.5	4.0	8.0	5.6	11.3	5.3	10.7
4	3.5	7.1	3.7	7.5	3.2	6.4	4.2	8.4	3.8	7.5

Table 9. *TPP Test Results of Two Layer Fabrics.*

Fabric	Tolerance time (TT), s	TPP, cal/cm2	TT, s	TPP, cal/cm2	TT, s	TPP, cal/cm2	TT, s	TPP, cal/cm2	TT, s	TPP, cal/cm2
	Before washing		1st washing		3rd washing		5th washing		10th washing	
1 + 5	7.1	14.2	9.0	17.9	9.8	19.7	9.7	19.4	9.9	19.8
2 + 5	7.6	15.2	12.0	23.9	10.4	20.7	10.8	21.6	9.9	19.7
3 + 5	7.3	14.6	8.0	16.0	8.4	16.8	11.2	22.3	9.2	18.4
4 + 5	7.0	14.0	8.0	16.0	8.5	17.0	9.8	19.6	10.6	21.2

Table 10. *TPP Test Results of Three Layer Fabrics.*

Fabric	Tolerance time (TT), s	TPP, cal/cm2	TT, s	TPP, cal/cm2	TT, s	TPP, cal/cm2	TT, s	TPP, cal/cm2	TT, s	TPP, cal/cm2
	Before washing		1st washing		3rd washing		5th washing		10th washing	
1 + 6	15.5	30.9	14.9	29.7	15.4	30.8	14.7	29.5	16.5	33.1
2 + 6	17.4	34.8	17.7	35.5	17.2	34.5	17.0	34.0	19.1	38.3
3 + 6	12.9	25.7	15.0	30.1	15.4	30.9	14.8	29.5	16.8	33.7
4 + 6	14.4	28.7	15.5	31.0	13.4	26.7	13.8	27.5	14.7	29.4

Table 11. *Tear Strengths of Fabrics Before and After Washing Cycles.*

Fabrics	Tear strength, N									
	Before washing		1st washing		3rd washing		5th washing		10th washing	
	warp	weft	warp	weft	warp	weft	warp	weft	warp	weft
1a	113	128	115	126	112	122	112	121	107	117
2a	174	160	157	171	169	147	160	151	147	146
3	62	56	65	51	61	51	62	50	57	51
4	52	52	47	49	42	43	43	43	41	43
5	27	23	22	19	15	14	13	11	13	11
6	-	-	-	-	-	-	-	-	-	-

[a] Some samples of these fabrics tear inappropriately.

study. The causes for this decrease may be the mechanical activity of the washing machine, and the chemicals in the detergents used in washing [15].

Conclusions

Our TPP test apparatus gives repeatable results. Differences from the Du Pont test results were expected because a spacer is used in the Du Pont tests for single layer fabrics. As explained in various literature sources and standards, the test results may vary slightly between laboratories.

The thermal analysis shows that the most important factors which influences the TPP ratings is the thickness and the fibre type of the fabrics. Also, area mass seems to be effective but is of less importance. An increased setting causes the heat to transfer by conduction. Using multi-layer assemblies increases the TPP ratings. The TPP ratings of three-layer structures are approximately 2.5-3.0 times those of the TPP ratings of single-layer fabrics. This is because the aramid felt in the three-layer assemblies substantially increases the total thickness of the assemblies and the amount of entrapped air. Therefore, the highest TPP ratings are obtained.

Washings decrease the tear strengths of the fabrics,and give them a compact structure. Air permeability exhibits more change than area mass or dimensional changes, which shows that fluffing may be occurring. Compactness has more effect on single layer fabrics, and causes a small decrease in the TPP ratings of single-layer fabrics. However fluffing, together with the increased amount of entrapped air in layers, is very common for assemblies, and causes an increase in the TPP ratings of assemblies after repeated washings.

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Received 05.04.2004 Reviewed 01.02.2005