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Heat Protection Potential of Fire-Fighters' Safety Clothing

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ABSTRACT

Heat and mechanical protection properties of six (6) fabric combinations commonly used in fire fighters' protection clothing were evaluated before and after different heat treatment. After heat exposure, it was shown that the values obtained were generally lower than the original state. More affected by heat were the mechanical properties of the materials than by heat protective properties. In two cases, depreciation started before a visible change in the material could be seen which might be potentially risky for the end user that will not notice the change in the material.

1. Introduction

The performance of a protective clothing system is of course evaluated for each new fabric combination. Nevertheless, the changes of the material over time are rarely considered, though these might decrease the level of protection and represent a potential risk to the user. Vogelpohi and Easter showed that used turnout coats showed decreased tensile strength, flame and water resistance [1]. It was shown that the water vapour permeability of membranes may reduce after exposure to heat [2-3]. A number of researchers made broad studies on the degradation of textiles and stated that molecular changes of fibres could happen during their lifetime and that the performance of the materials could be hindered long before the user noticed it as those changes were often not visible to the naked eye [4-10]. Efforts have been put up to trace the use of fire fighters protective clothing by observing the number of washing cycles of every piece of clothing, but it is important to evaluate a possible deterioration of materials during use [11-12].

The purpose of this study was to analyze the mechanical and the heat protection properties of fabric combinations used for firefighters protective clothing having been exposed to heat and flames. The samples were exposed to radiant of 40kw/m^2 or convective heat of 80kw/m^2 for specified periods. Tensile and tear strength and of course heat transfer were determined when exposed to radiant or convective heat.

2. Materials and Methods

A study of six different fabrics assemblies related to those used in fire-fighters protective clothing conforming to standard No. EN 469:2005 was studied (Table 1). Firstly, after five washing cycles according to standard No. ISO 6330:2000, procedure 2A at 60^{0}C, the characteristics of the heat protection of the assemblies was evaluated by measuring the time to reach temperature increase of 12 or 24^{0}C in a calorimeter (t_{12} and t_{24}, respectively) covered, with the samples (when either exposed to a radiant heat source of 40kw/m^2 or a convective heat source of 80kw/m^2 (table 2). These tests conformed to the requirements of standard No. EN 369:20005 and the test methods applied are of course described in standards No. ISO 6942:2002 and EN 367:1992 [13-15]. Moreover, the exposure time until a visible change happened in the outer shell was evaluated by an iterative process (exposure for a specified length of time) using method A of standards No. ISO 6942: 2002 or EN 367:1992. A visible change was evaluated as a discoloration of the material visible to the bare eyes [. A scanning electronic microscopy is also used to analyze some materials.

The combinations were then exposed to either a radiant or convective heat source for a specified time in order to stimulate thermal aging of the materials. The time t_{24} to reach a temperature increase of 24^{0}c was the longest exposure time for treating. After the heat exposure, the materials were again conditioned at 20^{0}C and 65% RH for at least 24hrs and different mechanical (tensile strength and tear resistance) [16-17] or thermal properties of the combinations were estimated. The results were given as mean values of the tested samples; standard deviation was estimated.

Moreover, a statistical analysis (T test) to estimate the importance of heat exposure - related changes was performed.

Table 1: Description of Fabric Combinations

Sample	Outer Shell	Surface Weight (g/m^2)	Water Barrier	Surface Weight (g/m^2)	Thermal Barrier	Surface Weight (g/m^2)	Total Weight (g/m^2)
1	PBI/aramid	210	PTFE membrane	145	aramid	110	465
2	aramid	265	PTFE membrane	145	aramid	130	540
3	aramid	210	PES membrane	130	aramid	290	630
4	arimid/basofil	245	PTFE membrane	135	aramid	290	670
5	aramid	190	PU membrane on aramid non-woven	215	aramid/FR viscose	170	575

6	aramid	250	PTFE membrane	135	aramid	345	730

Notes: PBI – Polybezimidazole fibre,
PTFE – Polytetrafluoroethylene,
PES - Polyster, PU – Polyurethane
FR - Flame retardant

Table 2: Time(s) to reach a temperature increase of 24^0C (t_{24}) or a colour change in the outer shell.

	Radiant Heat [14]			Convective Heat [15]		
Sample	t_{24}	t_{24}- t_{12}	Colour Change	t_{24}	$t_{24} - t_{12}$	Colour Change
1	28.9	8.6	10	24.6	6.6	5.0
2	21.3	6.3	10	16.5	4.0	2.0
3	32.1	8.8	6	24.2	6.0	1.5
4	28.9	7.3	7	29.3	8.1	3.0
5	24.9	7.0	6	19.2	4.6	1.5
6	33.4	9.8	9	27.4	8.0	2.5

Notes: t_{12} - time to reach a temperature increases of 12^0C.

3. Results and Discussion

3.1 Heat Protection

All the combinations used reached the limits of heat protection required by standard No. EN 469: 2005. Before the measurement of protection, all the samples were exposed to heat for a period conforming to t_{24}. The evaluation of heat protection times according to standards No. ISO 6942:2002 and EN 367:1992 after the initial heat treatment conformed to double heat exposure [18-20].

There was a decrease in the level of heat protection for all samples after thermal treatment, but exception for sample 6. This decrease was normally larger for convective heat exposure (Figure 1) than radiant heat (Figure 2).This result can be explained in that for high heat flux exposure, the combination of the fabric acts as a heat sink before heat is transferred to the inner layers and calorimeter. Hence, the temperature rise in the outer shell was much higher probably during convective heat exposure at 80kw/m^2 than during radiant exposure at 40kw/m^2. This probably also explain the fact that why sample 5 had the highest decrease in protection against convective heat (28.1%), as thin sample had the smallest surface weight of all the samples and was hence, damaged probably to a larger extent than the others during heat treatment. As all the samples had high protection levels, the limits of protection is specified in standard No. EN 496:2005 (performance level 2) were still reached ($t_{24} \geq 18.0$ and $t_{24} - t_{12} \geq 4.0$ for radiant heat; and $HTI_{24} \geq 13.0$ and $HTI_{24} - HTI_{12} \geq 4.0$ for convective heat) by all the samples except sample 2, which obviously had too low a time difference $HTI_{24} - HTI_{12}$ after treatment, though this sample showed the smallest decrease in heat protection of the all samples [21-23]. Sample 1 reached a little higher time difference $t_{24} - t_{12}$ after radiant heat treatment than the original state but result is characterized by uncertainty of measurement. For convective heat protection after heat treatment, Sample 6 reached better results.

This sample was totally burnt after the treatment that can have a positive influence on heat protection. Hence, as the burnt material becomes brittle, the material can no longer be used in practice after such heat exposure.

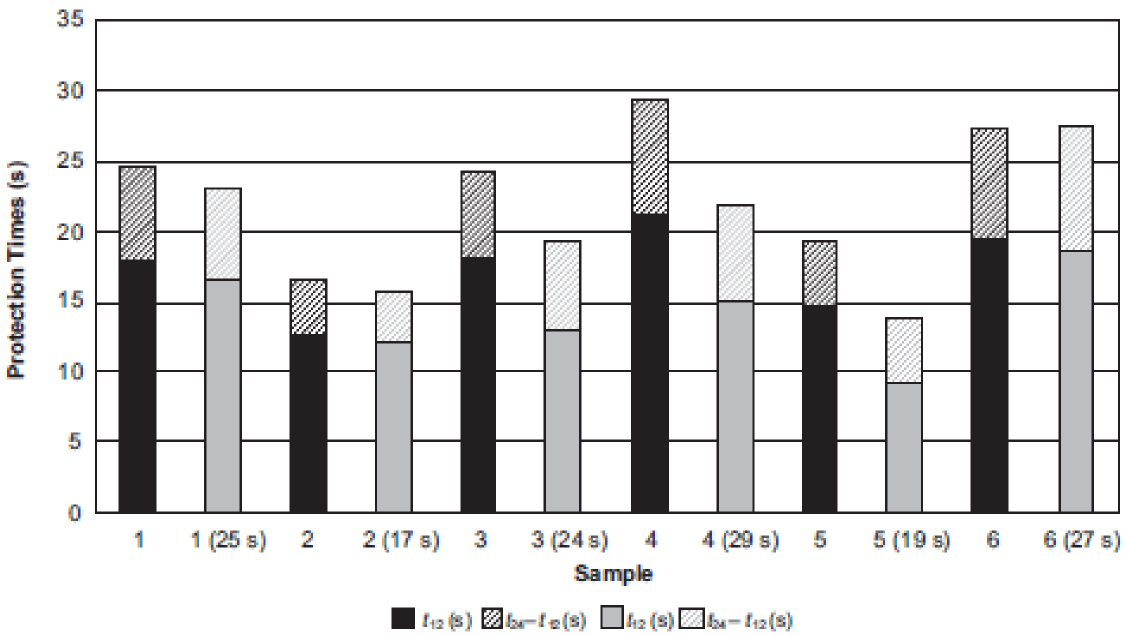

Figure 1. Times to reach a temperature increase of 12 and 24 °C (t_{12} and t_{24}, respectively) when exposed to a convective heat source (80 kW/m^2) [15] with and without thermal treatment (the times in brackets show the duration of the treatment).

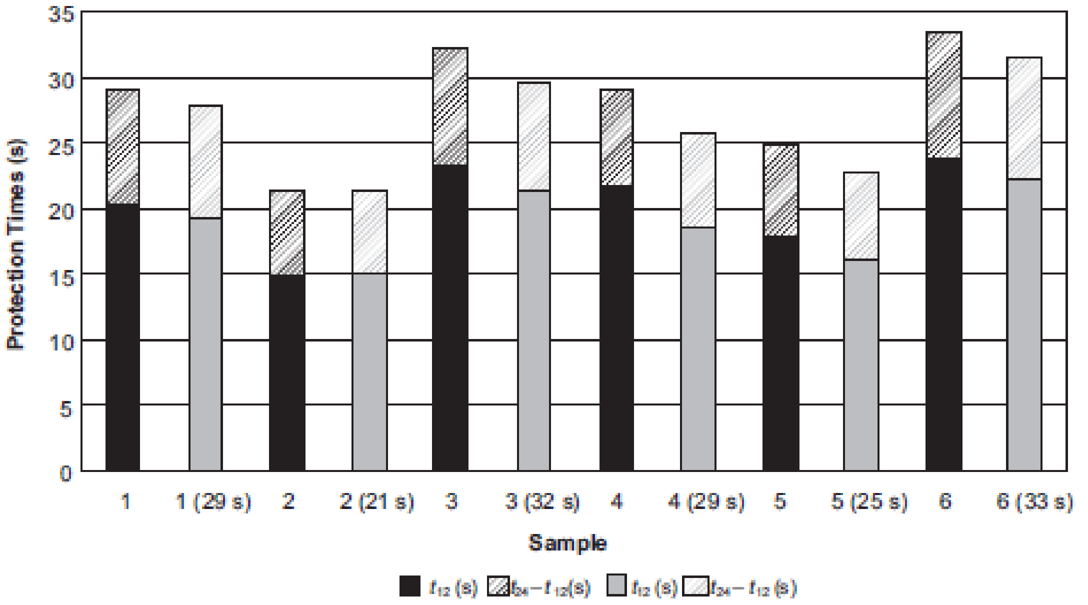

Figure 2. Times to reach a temperature increase of 12 and 24 °C (t_{12} and t_{24}, respectively) when exposed to a radiant heat source (40 kW/m^2) [14] with and without thermal treatment (the times in brackets show the duration of the treatment).

3.2 Mechanical Protection

The measurements of the tensile strength were made in the original state (after fire washings), and a heat treatment conforming to the necessary time to find a colour change in the outer layer (Table 3). Samples 3, 5, and 6 reached almost the same tensile strength after the heat treatment that shows that the mechanical integrity of these outer shell materials as of course retained till the change in the colour of this layer. The tensile strength of sample 4 remained constant after the radiant heat exposure but it was decrease by roughly 40% after the convective heat exposure. The measurement of thin sample was repeated with radiant heat exposure of 1s longer (8s) and tensile strength of 660N was obtained which confirms to a decrease of almost 50%. Sample 4 showed a large reduction of mechanical strength close to the point of decolouration.

Sample 1, a decrease in tensile strength of about 40% after the radiant heat treatment and of course, about 60% after the convective heat treatment. Changes in the molecular structure as a result of thermal load must happen before a change becomes noticed to the bare eye in this material. The sample was analyzed with the help of a scanning electron microscope (AmRay 3200C ECO-SEM: KLA Tencor, USA), but in the structure of the fibre, no visible changes is noticed. Hence, it could be assumed that the changes must come from breaking of the chains of the polymer on the molecular level, but no further investigation was carried out on this hypothesis. Some measurements were however made with this material when treated to shorter heat exposures and confirmed that part of the decrease in tensile strength took place already before the limit of colour change was reached [24-26].

Sample 2 also had a decrease in tensile strength, that was much smaller (-11% after both radiant and convective heat treatments) than sample 1. A statistical analysis (T test) showed that the decrease in tensile strength was not significant for sample 2 (P = 1 for radiant heat treatment) and the scattering was of course high. As the times of treatment were different and as sample 1 and 2 were the ones with the longest times of treatment, the tensile strength of all the samples was evaluated after a fixed radiant heat exposure of 7s to analyze if the decrease in strength happened after a similar heat exposure for all samples.

Sample 3, 4, 5 and 6 did not show any decrease in tensile strength after heat exposure showing that the mechanical integrity of the bulk material looked not to be affected by this heat load and the decolouration of the samples was may be due to chemical changes in the dye only. In standard No. EN 469: 2005, the lower limit for tensile strength is set at 450N, that was still reached easily by the samples even after the treatment.

Table 3: Tensile Strength (N) Before and After Heat Treatment

	Radiant Heat Treatment			Convective Heat Treatment		
	Tensile Strength				Tensile Strength	
Sample	Treatment (s)	Before	After	Treatment (s)	Before	After
1	10	2095± 61	1263 ± 67	5.0	2095 ± 61	850 ± 48
2	10	2292 ± 144	2047 ± 234	2.0	2292 ±144	2037 ± 151
3	6	1180 ± 17	1163 ± 6	1.5	1180 ± 17	1163 ± 15
4	7	1323 ± 49	1223 ± 81	3.0	1323 ± 49	798 ± 168
5	6	1157 ± 14	1180 ± 17	1.5	1157 ± 14	1147 ±12
6	9	1586 ±13	1557 ± 35	2.5	1586 ± 13	1573 ± 21

The tear resistance measurements according to standard No. ISO 4674-1:2003 showed results similar to the tensile strength (Table 4): Samples 3 and 5 with the shortest treatment of heat reached almost the same value as the original fabrics. Sample 1 and 2 had the highest original values, but also the largest decrease after the thermal treatments; after 10s exposure, samples 1 and 2 obtained 48 and 65 N respectively that conformed to a decrease of 61 and 47% respectively. After 5s convective (heat treatment, the drop was even greater for 1 (-79%) and the required limit by standard No. EN:469:2005 (25N) was almost reached. For sample 2, the decrease was much smaller (-14%) as heat exposure lasted only for 2s. The degradation of Sample 4 started right at the point of decolouration: when the sample was exposed for 1s less than the time for decolouration (i.e 6s of radiant heat or 2s of convective heat), the same values were obtained for the non-treated samples. Hence, if exposure was longer, tear resistance was strongly reduced (-24% after 7s of radiant heat exposure, -33% after 3s of convective heat) and fell below the required limit by standard No EN 469:2005 when exposed 1s longer than the time for colour change (i.e 22N after 8s radiant heat treatment and 23N after 4s of convective heat) the high standard deviation of the tear strength after convective treatment for sample 4 shows also that the degradation took place right at 3s of heat exposure: some of the samples were more or less complete after this exposure while others were already damaged, interpreting the large spreading of results. Sample 6 also showed an important reduction in tear resistance (-26%) after 9s of exposure of radiant heat. There was also a reduction of (-13%) after2.5s of convective heat, but these values still were above the limit in Standard No EN 469:2005, and even when exposure was 1s longer than the time for colour change.

Table 4: Tear Strength (N) Before and After Heat Treatment

	Radiant Heat Treatment			Convective Heat Treatment		
	Tear Strength				Tear Strength	
Sample	Treatment (s)	Before	After	Treatment (s)	Before	After
1	10	123 ± 5	48 ± 6	5.0	123 ± 5	25 ± 4
2	10	122 ± 17	65 ±17	2.0	122 ± 17	105 ± 4
3	6	27 ± 3	26 ± 1	1.5	27 ± 3	26 ± 1
4	7	75 ± 4	57 ± 5	3.0	75 ± 4	50 ± 24
5	6	29 ± 1	30 ± 1	1.5	29 ± 1	29 ± 1
6	9	53 ± 6	39 ± 1	2.5	53 ± 6	46 ± 3

4. Conclusion

The heat and mechanical protection properties of six different fabric combinations used for fire fighters protective clothing were evaluated before and after thermal aging. The performance of the samples was normally decreased after heat exposure but in many cases, the required limits in the standard for firefighters' protective clothing [12] were still reached, Hence, the thermal deterioration of the materials used in these samples seemed to begin before a change in the material was noticed.

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