

Performance of Firefighters' Protective Clothing After Heat Exposure

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Heat and mechanical protection properties of 6 fabric combinations commonly used in firefighters' protective clothing were assessed before and after different heat treatment. It was shown that after heat exposure, the values obtained were generally lower than in the original state. The mechanical properties of the materials were more affected by heat than by heat protective properties. In 2 cases, degradation started before a visible change in the material could be observed, which might be potentially dangerous for the end user who will not realize the alteration of the material.

heat protective clothing thermal ageing mechanical resistance heat protection

1. INTRODUCTION

The performance of a protective clothing system is usually assessed for each new fabric combination. However, the material changes over time are rarely considered, though these might reduce the level of protection and represent a potential hazard to the user. Vogelpohl and Easter [1] showed that used turnout coats showed reduced tensile strength, flame and water resistance. Another study [2] showed that the water vapour permeability of membranes may decrease after heat exposure. Slater et al. made extensive studies on the deterioration of textiles [3, 4, 5, 6, 7, 8, 9] and stated that molecular changes of fibres could occur during their lifetime and that the functionality of the materials could be impaired long before the user realized it as those changes were often invisible to the naked eye. Efforts have been undertaken to trace the use of firefighters' protective clothing by monitoring the number of washing cycles of each piece of clothing [10, 11], but it is nontrivial to assess a possible degradation of materials during use.

The aim of this study was to analyse the mechanical as well as the heat protection properties of fabric combinations used for firefighters' protective clothing after exposure to heat and flames. The samples were exposed to either radiant (40 kW/m²) or convective heat (80 kW/m²) for defined periods. Tensile and tear strength, as well as heat transfer when exposed to radiant or convective heat, were then determined.

2. METHODS

Six different fabric assemblies typical for those used in firefighters' protective clothing corresponding to Standard No. EN 469:2005 [12] were studied (Table 1). First, after five washing cycles according to Standard No. ISO 6330:2000 [13], procedure 2A at 60 °C [13], the heat protection characteristics of the assemblies was determined by measuring the times to reach a temperature increase of 12 or 24 °C in a calorimeter (t_{12} and t_{24} , respectively) covered with the samples when exposed either to a radiant heat source of 40 kW/m² or a convective heat source of

80 kW/m² (Table 2). These tests corresponded to the requirements of Standard No. EN 469:2005 [12] and the test methods applied are described in Standards No. ISO 6942:2002 [14] and EN 367:1992 [15]. Furthermore, the exposure time until a visible change occurred in the outer shell was determined by an iterative process (exposure for a defined length of time) using method A of Standards No. ISO 6942:2002 or EN 367:1992. A visible change was determined as a decolouration of the material visible to the naked eye. Some materials were also analysed with scanning electronic microscopy.

In order to simulate thermal ageing of the materials, the combinations were then exposed

to either a radiant or a convective heat source for a defined time. The time t_{24} to reach a temperature increase of 24 °C was the longest treating exposure time. After the heat exposure, the materials were conditioned again at 20 °C and 65% RH for at least 24 hrs and different mechanical (tensile strength [16] and tear resistance [17]) or thermal properties of the combinations were then assessed. The results were given as mean values of the samples tested; standard deviation was also determined. Furthermore, a statistical analysis (T test) to determine the significance 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	aramid/basofil	245	PTFE membrane	135	aramid	290	670
5	aramid	190	PU membrane on aramid nonwoven	215	aramid/FR viscose	170	575
6	aramid	250	PTFE membrane	135	aramid	345	730

Notes. PBI—polybenzimidazole fibre, PTFE—polytetrafluoroethylene, PES—polyester, PU—polyurethane, FR—flame retardant.

TABLE 2. Time (s) to Reach a Temperature Increase of 24 °C (t_{24}) or a Colour Change in the Outer Shell

Sample	Radiant Heat [14]			Convective Heat [15]		
	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 increase of 12 °C.

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 [12]. Prior to the measurement of heat protection, all samples were exposed to heat for a period corresponding to t_{24} . The determination of the heat protection times according to Standards No. ISO 6942:2002 [14] and EN 367:1992 [15] after the initial heat treatment thus corresponded to double heat exposure.

There was a reduction in the level of heat protection for all samples after thermal treatment, except for sample 6. This reduction was generally larger for convective heat exposure (Figure 1) than for radiant heat (Figure 2). This result can be explained by the fact that for high heat flux exposure, the fabric combination acts as a heat sink before heat is transferred to the inner layers and to the calorimeter. Therefore, the temperature rise in the outer shell was probably much higher during convective heat exposure at 80 kW/m^2 than during radiant heat exposure at 40 kW/m^2 . This fact probably also explains why sample 5

had the highest reduction in protection against convective heat (28.1%), as this sample had the smallest surface weight of all samples and was therefore probably damaged to a greater extent than the others during heat treatment. As the samples all had quite high protection levels, the limits of protection as defined in Standard No. EN 469:2005 [12] (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 for sample 2, which apparently had too low a time difference $HTI_{24} - HTI_{12}$ after treatment, although this sample showed the smallest reduction in heat protection of all samples. Sample 1 reached a slightly higher time difference $t_{24} - t_{12}$ after radiant heat treatment than in the original state, but this result lies within the uncertainty of measurement. Sample 6 reached better results for convective heat protection after heat treatment. This sample was completely charred after the treatment, which can in general have a positive influence on heat protection. However, as the charred material becomes brittle, this material could no longer have been used in practice after such heat exposure.

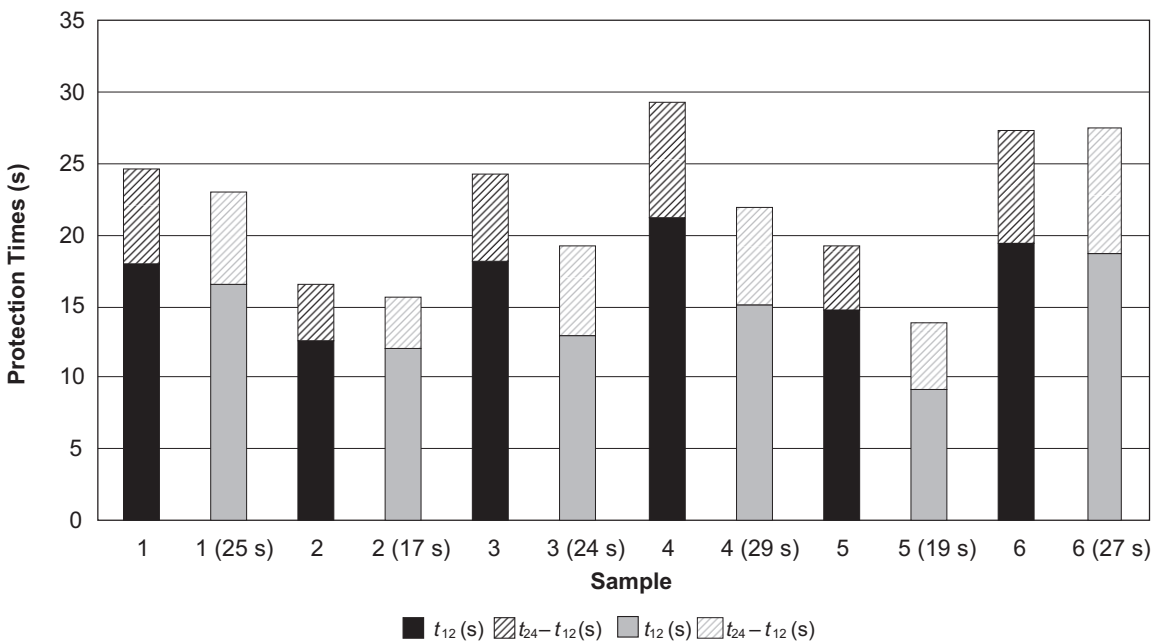


Figure 1. Times to reach a temperature increase of 12 and 24 °C (t_{12} and t_{24} , respectively) when exposed to a convective heat source (80 kW/m^2) [15] with and without thermal treatment (the times in brackets show the duration of the treatment).

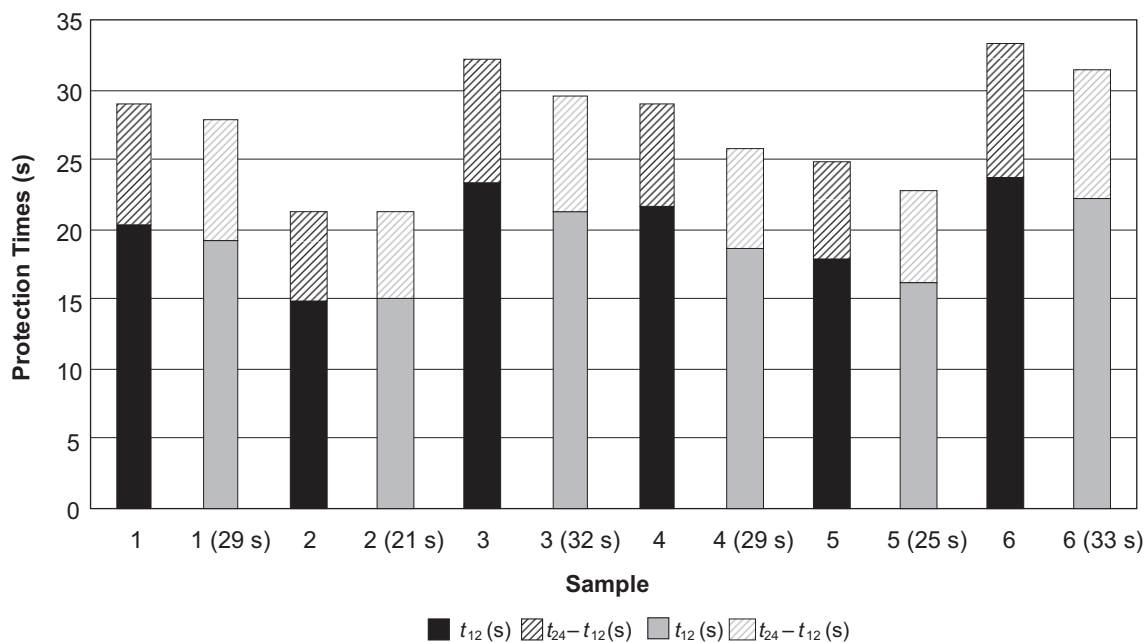


Figure 2. Times to reach a temperature increase of 12 and 24 °C (t_{12} and t_{24} , respectively) when exposed to a radiant heat source (40 kW/m²) [14] with and without thermal treatment (the times in brackets show the duration of the treatment).

3.2. Mechanical Protection

The measurements of the tensile strength were made in the original state (after five washings), as well as after a heat treatment corresponding to the time necessary to detect a colour change in the outer layer (Table 3). Samples 3, 5, and 6 reached about the same tensile strength after the heat treatment, which shows that the mechanical integrity of these outer shell materials was maintained until the change in the colour of this layer. The tensile strength of sample 4 remained more or less constant after the radiant heat exposure but it was reduced by about 40% after the convective heat exposure. The measurement for this sample was repeated with radiant heat exposure of 1 s longer (8 s) and tensile strength of 660 N was obtained, which corresponds to a reduction of nearly 50%. Sample 4 thus showed a large decrease of mechanical strength near the point of decolouration.

Sample 1 showed a reduction in tensile strength of about 40% after the radiant heat treatment and about 60% after the convective heat treatment. In this material, changes in the molecular structure due to the thermal load must occur before a change becomes visible to the naked eye. The sample was analysed with a scanning electron

microscope (AmRay 3200C ECO-SEM; KLA Tencor, USA), but no visible changes in the structure of the fibres could be noticed. Therefore, it may be assumed that the changes must come from breaking of the polymer chains on the molecular level, but this hypothesis was not further investigated. Some measurements were made with this material when treated to shorter heat exposures and confirmed that part of the reduction in tensile strength already took place before the limit of colour change was reached. Sample 2 also had a reduction in tensile strength, which was, however, much smaller (–11% after both radiant and convective heat treatments) than for sample 1. A statistical analysis (*T* test) showed that the reduction in tensile strength was not significant for sample 2 ($p = .1$ for radiant heat treatment) and the scattering of results was high. As the treatment times were different and as samples 1 and 2 were the ones with the longest treatment times, the tensile strength of all the samples was assessed after a fixed radiant heat exposure of 7 s to analyse whether the reduction in strength occurred after a similar heat exposure for all samples.

Samples 3, 4, 5 and 6 did not show any reduction in tensile strength after this heat

TABLE 3. Tensile Strength (N) Before and After Heat Treatment

Sample	Radiant Heat Treatment			Convective Heat Treatment		
	Treatment (s)	Tensile Strength		Treatment (s)	Tensile Strength	
		Before	After		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

exposure showing that the mechanical integrity of the bulk material seemed not to be affected by this heat load and that the decolouration of the samples was probably due to chemical changes in the dye only. In Standard No. EN 469:2005 [12], the lower limit for tensile strength is set at 450 N, which was still easily reached by all samples even after the treatment.

The measurements of tear resistance according to Standard No. ISO 4674-1:2003 [17] showed results similar to the tensile strength (Table 4): samples 3 and 5 with the shortest heat treatment reached about the same values as the original fabrics. Samples 1 and 2 had the highest original values, but also the largest decrease after the thermal treatment: after 10-s exposure, samples 1 and 2 obtained 48 and 65 N, respectively, which corresponded to a reduction of 61 and 47%, respectively. After 5-s convective heat treatment, the drop was even greater for sample 1 (−79%) and the limit required by Standard No. EN 469:2005 [12] (25 N) was almost reached. For sample 2, the reduction was much smaller (−14%), as heat exposure only lasted for 2 s. The degradation of sample 4 started right at the point

of decolouration: when this sample was exposed for 1 s less than the time for decolouration (i.e., 6 s of radiant heat or 2 s of convective heat), the same values were obtained as for the nontreated samples. However, if exposure was longer, tear resistance was strongly reduced (−24% after 7 s of radiant heat exposure, −33% after 3 s of convective heat) and fell below the limit required by Standard No. EN 469:2005 [12] when exposed 1 s longer than the time for colour change (i.e., 22 N after 8-s radiant heat treatment and 23 N after 4 s of convective heat). The high standard deviation of the tear strength after convective heat treatment for sample 4 also shows that the degradation took place right at 3 s of heat exposure: some of the samples were still more or less intact after this exposure while others were already damaged, explaining the large spreading of results. Sample 6 also showed a significant decrease in tear resistance (−26%) after 9 s of radiant heat exposure. There was also a decrease (−13%) after 2.5 s of convective heat, but these values were still above the limit in Standard No. EN 469:2005, even if exposure was 1 s longer than the time for colour change.

TABLE 4. Tear Strength (N) Before and After Heat Treatment

Sample	Radiant Heat Treatment			Convective Heat Treatment		
	Treatment (s)	Tear Strength		Treatment (s)	Tear Strength	
		Before	After		Before	After
1	10	123 ± 5	48 ± 6	5.0	123 ± 5	26 ± 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. CONCLUSIONS

The heat and mechanical protection properties of six different fabric combinations used for firefighters' protective clothing were assessed before and after thermal ageing. The performance of the samples was generally reduced after heat exposure, but in most cases, the limits required in the standard for firefighters' protective clothing [12] were still reached. Two of the six samples showed a reduction in mechanical strength before the time for a decolouration in the outer shell was reached. Therefore, the thermal degradation of the materials used in these samples seemed to start before there was a visible change in the material.

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