Radiant Protective and Transport Properties of Fabrics Used by Wildland Firefighters

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ABSTRACT

The radiant protective performance, thermal resistance, air permeability, and moisture evaporation of a series of fabrics made from aramid, modacrylic, polyimide, and fire resistant cotton fibers are evaluated in the laboratory. The radiant protective performance of single-layer fabrics is affected by the structure, weight, thickness, and materials, consistent with the thermal protective performance of fabrics previously discussed. A fabric's transport properties, which are closely associated with comfort performance, can be reflected by a combination of its air permeability, thermal resistance, and moisture evaporation, which are also governed by the same structural factors. Thus, it is our intention to explore the relationship between fabric structures and both radiant protective and transport properties so that we can provide the necessary information for selecting appropriate fabrics for firefighter's uniforms.

Maximizing thermal protection from fire and minimizing metabolic heat stress are two major conflicting factors to consider in developing protective clothing for wildland firefighters [2, 6, 12, 14], and both radiant heat and heat stress can cause injuries or health problems to firefighters [6]. High thermal protection can be achieved by wearing multilayered or thick textile materials, but this prevents good ventilation and so creates high heat stress to wearers, reducing their work efficiency in battles against wild fires. The California Department of Forestry and Fire Protection currently requires wildland firefighters to wear two layers of clothing during fire fighting operations. This practice was developed in response to evidence that extra clothing layers provide additional protection against burn injuries. As a result, however, lower productivity and longer or more frequent rests would be needed for firefighters to alleviate fatigue and body-generated heat stress.

The human body itself is a heat-generating system due to its metabolic activities that maintain a balance between heat loss and heat gain, thus achieving the narrow range of internal temperatures desirable for the body. Many environmental factors such as the temperature and velocity of the surrounding air, heat radiation, and humidity will affect that balance [5, 7, 10, 13]. If clothing materials and the structure of the garments can allow evaporation of perspiration and ventilation in addition to thermal protection, this will also affect the heat balance of the body [1]. As firefighters are battling fires, external heat sources like radiant heat from the fire or the sun and internal heat produced by energy expenditures can easily upset the body balance and cause overheating. Thus, it is necessary that the clothing be a good barrier to external heat and at the same time a proper conductor for internal heat. These two seemingly contradictory requirements cause great difficulty in selecting suitable fabrics for uniforms.

Evaluations of wildland firefighter clothing regulations and practices, as well as development of new prototypes, should therefore be based on these competing requirements of adequate thermal protection, adequate mobility, and low physiological stress. The traditional view of fire fighting protective clothing may have put too much emphasis on the thermal protection aspect, and underestimated or ignored other important aspects of the garments [14]. The National Fire Protection Association (NFPA) 1977 standard on protective clothing and equipment for wildland fire fighting [11] reflects a broadening of criteria for protective clothing. Our research on evaluating firefighters' uniforms and their design is intended to explore the relationships between fabric structures, numbers of fabric layers, and their effects on thermal protective and transport properties. In this article we use radiant protective performance and transport properties such as air permeability, vapor evaporation, and thermal resistance of single-layer fabrics commonly used by wildland firefighters to discuss their combined effect on both radiant-heat thermal protection and comfort performance, and we lay the groundwork for understanding the performance of multilayer combinations. We also discuss the impact of color differences of outer layers, their thickness or weight, and their structural features on radiant protective performance values and thermal resistance.

Experimental

The basic technical descriptions of fabrics used in the study are provided in Tables I and II, including synthetic fire-resistant fibers such as Nomex®, Kermel®, Firewear®, fire-resistant (FR) cotton, and cotton blends that are commonly used in wildland fire protective and station clothing.

Radiant Protective Performance (RPP): We set up the RPP tester according to the NFPA standard 1977, standard in protective clothing and equipment for wildland fire fighting [11], using five 500-watt quartz tubes as a heat source. The heat flux of the source was calibrated to 0.5 cal/cm^2 · s. The temperature response versus time change was detected by a copper calorimeter located behind the sample fabrics at a distance of 2.54 cm (1 inch) to the surface of the quartz tubes; the signal in mV was recorded on a plotter. The quartz tubes were preheated for 60 seconds before they were exposed to the fabric samples. Exposure time for fabrics was 25 seconds for a

TABLE I. RPP values and structural features of selected fabrics.

		Fabric properties			RPP values, cal/cm^2	
Sample	Material	Structural feature	Weight, mg/cm^2	Thickness, mm	Before washing	After five washes
A-1	Nomex IIIa	yellow basket	18.65	0.554	8.01 ± 0.28	8.25 ± 0.34
A-2	Nomex IIIa	yellow poplin	18.65	0.358	7.98 ± 0.18	7.92 ± 0.55
A-3	Nomex IIIa	yellow poplin	20.35	0.505	7.71 ± 0.22	8.60 ± 0.52
A-4	Nomex IIIa	yellow check	20.35	0.597	7.57 ± 0.04	8.00 ± 0.34
A-5	Nomex IIIa	green twill	28.82	0.729	9.37 ± 0.49	10.37 ± 0.74
A-6	Nomex IIIa	blue twill	28.82	0.701	10.60 ± 0.74	10.88 ± 0.41
C-1	FR cotton	white twill	23.74	0.561	8.95 ± 0.20	9.02 ± 0.41
C-8	cotton	white knit	16.96	0.569	8.11 ± 0.31	9.32 ± 0.33
C-2	cotton/nylon 88/12	blue twill	25.43	0.500	7.24 ± 0.89	8.45 ± 0.28
C-10	poly/cotton 40/60	brown twill	25.43	0.439	8.80 ± 0.07	8.81 ± 0.25
B-3	Firewear	green twill	30.52	0.523	10.08 ± 0.38	10.49 ± 0.89
B-5	Kermel 260	blue twill	23.74	0.488	7.42 ± 0.21	7.54 ± 0.33
B-7	Kermel	navy blue twill	25.43	0.531	6.93 ± 0.11	7.52 ± 0.61
B-8	Kermel	navy blue knit	18.65	0.935	6.18 ± 0.42	6.45 ± 0.10
B-4	Kevlar/PBI 60/40	yellow twill	15.26	0.434	6.22 ± 0.14	7.56 ± 0.03

TABLE II. RPP values and structure characteristics of Nomex fabrics.

	Fabric properties				RPP values, cal/cm²	
Sample	Structural feature	Color	Weight, mg/cm²	Thickness, mm	Before washing	After five washes
N-1	plain	yellow	15.26	0.438	6.50	–
N-2	plain	tan	15.26	0.460	6.71	–
N-3	plain	spruce	15.26	0.439	6.52	–
N-4	plain	gulf blue	20.35	0.500	7.88	–
N-5	plain	red	15.26	0.465	6.58	–
N-6	plain	orange	15.26	0.467	6.50	–
N-7	plain	navy blue	15.26	0.445	6.56	6.60
N-8	plain	navy blue	20.35	0.511	8.20	8.13
N-9	plain	navy blue	25.43	0.597	9.04	9.13
N-10	jersey knit	khaki	22.04	0.592	8.01	8.02
N-11	interlock	navy blue	30.52	0.968	9.34	9.00

single layer and relatively longer for multilayer samples. The time T in seconds to cause a second-degree skin burn of each sample fabric was determined by overlaying the curve of the thermal response of the calorimeter with a curve obtained from ASTM standard test method D 4108 in the same time scale. Fabric samples, both pre-washed and after five washes, were preconditioned in a conditioning room (21°C and 65% RH) before RPP testing. The RPP value is calculated according to the following equation:

$$RPP = 0.5 \times T \quad .$$

Thermal Resistance: The thermal resistance test was also conducted according to the same NFPA standard 1977 [11] and ASTM D-1518. The tester was prepared according to illustrations in ASTM test method D-1518. Sweating tests recommended by NFPA 1977 were not performed by this tester. The average intrinsic thermal resistance of a sample fabric can be determined by subtracting the average bare plate resistance from the average of the total thermal resistance of the specimens tested. The total thermal resistance (R_{ct}) of the fabric in this study was calculated from the following equation:

$$R_{ct} = (T_s - T_a)A/H \quad ,$$

where R_{ct} = total thermal resistance of the specimen and surface air layer (°C/m²/W), T_s = temperature at the plate surface (°C), T_a = temperature in the local environment (°C), A = area of the test plate (m²), and H = power input (W).

Moisture Evaporation was determined using a conventional dish method at a constant temperature and relative humidity [9]. In the test, a given amount of distilled water was enclosed in a plastic beaker that was then sealed by a piece of fabric. The whole assembly was kept in a conditioning room (21°C and 65% RH). Water vapor permeability was calculated from the curve of the slope of water loss versus time. We tested only those fabric samples that could be used as outer layers of uniforms. Each measurement was made in triplicate or more.

Air Permeability: This test determined the rate of air flow through a fabric under a differential pressure between the two fabric surfaces by the calibrated orifice technique according to the ASTM D 737-75. The instrument was the air flow tester, model 9025, by USTC, Inc., and the test results were in m³/min/m², the volume of air passing through the fabric of unit area in 1 minute.

Differential Scanning Calorimeter (DSC) analysis of the fabrics was conducted on a Shimadzu DSC spectrometer with a heating speed of 20°C/minute in nitrogen to observe the thermal behavior of a specimen during RPP testing.

Results and Discussion

Many researchers have studied thermal protective performance (TPP) of single layer heat-resistant fabrics [3, 4, 8, 12]. Most measurements involved protocols with heat levels ranging from 0.2 to 2.0 cal/cm² · s of convective heat or mixed convective and radiant heat sources [12]. These testing conditions simulated a variety of hazardous environments from very limited radiant exposure to an intensified thermal source. However, the latest NFPA regulations recommend the RPP test as a standard method for evaluating clothing materials for wildland firefighters. As mentioned earlier, the RPP test uses a bank of quartz lamps with a heat flux of 0.5 cal/cm² · s as the radiant heat source. This heat source mainly emits radiant energy, which is more similar to the environment of wildland firefighting.

RPP VALUES OF DIFFERENT FABRICS

We measured single-layer radiant protective performance for all fabrics in terms of RPP values according to the NFPA standard test method [11]. The results of selected fabrics such as Nomex, Firewear, Kermel, poly/cotton, and FR cotton, together with other structural properties, are shown in Table I.

Examining RPP values in Table I, we find that thick and heavy-weight fabrics exhibit high radiant heat, indicating that, as expected, radiant protection of fabrics improves as their thickness or weight increases. Cotton materials tend to perform better than synthetics at the same weight or thickness, possibly due to their hollow fiber structure. Firewear fabric, a blend of fire-resistant modacrylic and cotton, and cotton blends of synthetic fibers such as nylon or polyester exhibit reasonably high RPP values. But we observed that most Firewear fabrics became charred during the RPP tests due to thermal decomposition, while fabrics containing synthetic fibers hardened because the polymers melted in the areas exposed to radiant heat. Nomex and FR cotton fabrics, on the other hand, showed no visible damage during the test. The colors on Kermel fabrics were completely faded in the areas exposed to radiant heat because of dye sublimation or decomposition, while the fabrics were still intact. After five washing cycles, most fabrics showed increased RPP values, possibly caused by increased thickness due to fuzzier surfaces created during laundering.

In order to examine the effects of fabric weight, structure, and color on RPP values, we selected a series of Nomex IIIa fabrics (supplied by Southern Mills, Atlanta, GA), which were manufactured specifically by altering the weaving structure, color, and weight. The structural features and RPP values of these fabrics are shown in Table II.

Comparing the data in Table II, we find that color has no significant effect on RPP values of the fabrics in the tested color variations. However, white and black color, the two extreme cases, were not included in the tests, and they may produce greater differences in radiant protective performance because of different reflection and absorption to radiant heat. Fabric weight and thickness have a direct impact on RPP values, heavier or thicker fabrics leading to higher RPP values, consistent with the results of other researchers [12]. Plotting RPP values versus fabric weight and thickness shows a linear correlation between properties and structural characteristics (Figures 1 and 2). Plain woven structures in general performed better than knitted structures with similar weights or thicknesses (compare fabrics N-8, N-9, N-10, and N-11 in Table II). Given the accepted minimum requirement of RPP = 8 [11] and its direct relationship with fabric weight shown in Figure 1, it is clear that 18.65 mg/cm^2 is the minimum weight for Nomex woven fabrics that can achieve or exceed the minimum RPP value.

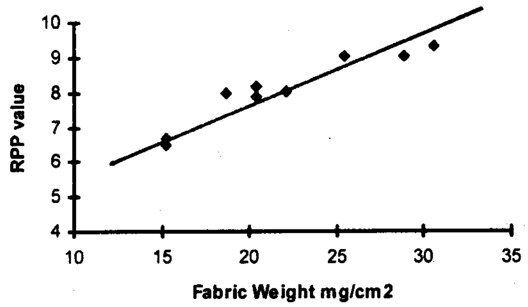

FIGURE 1. Effect of fabric weight on RPP values.

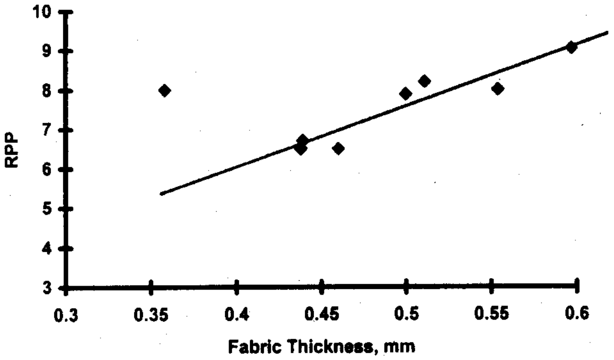

FIGURE 2. Effect of thickness on RPP values.

TYPICAL CALORIMETER RESPONSES FROM SINGLE-LAYER FABRICS

Typical calorimeter responses of some single-layer fabrics under the standard radiant heat source of 0.5 cal/cm^2 · s during the RPP test are plotted in Figure 3. The thermal responses of the fabrics have a similar pattern, that is, the initial portion of the curve is linear and then the slope changes as heat exposure continues. The slight slope change, varying in several stages during the testing process, results in reduced RPP values for most of the samples. We believe such reduced RPP values during exposure to the radiant heat source are attributable to several factors, such as thermal resistance, air permeability, porosity, thickness, thermal stability, and chemical structures of the fabrics, which have a direct or indirect impact on the thermal insulation properties of textile materials. These factors may jointly contribute to the slope changes at one or several stages. Obviously, understanding the changes during exposure to radiant heat

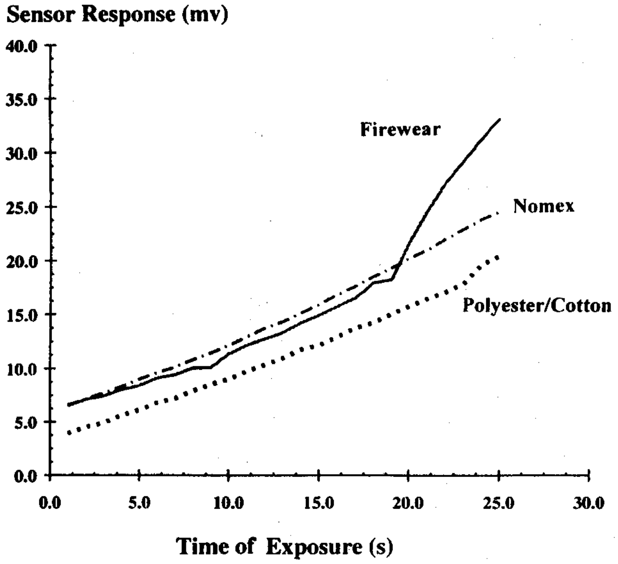

FIGURE 3. Typical calorimeter sensor responses from single-layer fabrics.

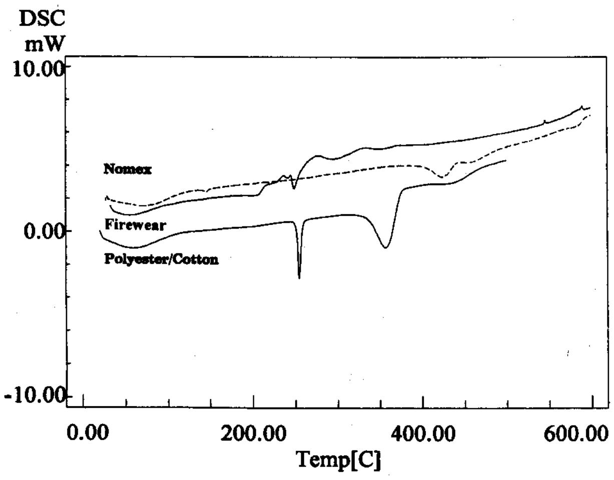

FIGURE 4. DSC spectra of three fabrics.

is necessary and will help us to develop an efficient clothing system for firefighters.

The slope changes in reduction mode can be called "yielding" of radiant heat protective performance during exposure to the radiant heat. At low temperature ranges or short exposure times, other physical structural factors play dominant roles, thus causing the yielding effect. But at a high temperature range, the thermal properties of polymers, such as melting points and decomposition temperatures, may have a critical affect on radiant protective performance. The DSC spectra of three typical fabrics, Nomex, poly/cotton, and Firewear containing modacrylic fibers, are shown in Figure 4. Nomex has no major thermal exchange in the temperature range of 200–400°C or exposure time of 15–25 seconds, polyester has an endothermic peak at about 240°C, and Firewear starts to have an exothermic exchange at below 200°C, indicating some thermal damage to the fabrics. Pure cotton and Nomex, both being thermally stable materials under 300°C, do not experience obvious thermal damage when visually examined after testing. The slight slope change of Nomex fabrics may refer to factors other than thermal stability, because there is no thermal property change indicated by DSC in the temperature range. In general, the thermal behaviors of the fabrics tested by RPP and DSC are consistent and correlated.

One explanation of the slope change could be forced convection during the RPP test. Although the RPP method is designed to test the protective performance of fabrics against radiant heat, during the test huge heat energy creates a pressure difference between both sides of the fabric and consequently induces forced convection (forced air flow through the fabric transporting thermal energy). This heat convection is obviously related to air permeability, fabric porosity, and layering. Determining all of the factors affecting the RPP values may require more extensive testing of the structural properties, which is still underway in our laboratories. We will report related developments in later articles.

TRANSPORT PROPERTIES OF SINGLE-LAYER FABRICS

Transport properties of single-layer fabrics include total thermal resistance or thermal conductivity, vapor evaporation, and air permeability, which are related to comfort performance. Thermal resistance and vapor evaporation can indicate internal to external thermal and moisture transport properties of the materials, *i.e.*, how well the material can pass body heat and moisture to the environment. Air permeability can reveal the breathing or ventilation functions of the materials. The comfort performance of fabrics can be evaluated fundamentally by a combination of these properties. Structural features and physiological properties are provided in Table III for some selected fabric samples and in Table IV for all tested Nomex fabrics.

The air permeability of different fabrics depends on their structure, *i.e.*, a loose, thin, porous structure will have a high air permeability, and vice versa. Under the same conditions, knit fabrics are more air permeable than woven fabrics, and plain woven structures are more air permeable than twills in general, as confirmed by the tables.

A fabric's total thermal resistance is an index of how well it will conduct heat, which is closely related to the

TABLE III. Transport properties of selected fabrics.

Sample	Fabric properties: Structural feature	Weight, mg/cm²	Thickness, mm	Transport properties: Thermal resistance, °C/m²/W	Vapor evaporation, g/m² h	Air permeability, m³/min/m²
C-1	FR cotton twill	23.74	0.561	0.171	45.33	47.55
C-4	P/C plain	30.52	0.759	–	47.04	20.76
C-6	P/C plain	8.48	0.246	–	54.77	157.64
C-8	cotton knit	16.96	0.569	–	50.85	155.45
C-9	cotton knit	20.69	0.777	–	48.24	112.01
C-10	P/C twill	21.70	0.439	0.159	50.35	39.32
C-13	cotton denim	50.87	1.013	–	45.13	20.30
B-3	Firewear twill	30.52	0.523	0.163	52.36	20.30
B-4	Kevlar/PBI twill	15.26	0.434	–	49.65	94.00
B-5	Kermel twill	23.74	0.488	–	47.34	37.31
B-7	Kermel twill	25.43	0.531	–	39.9	28.16
A-1	Nomex	18.65	0.554	0.161	53.47	66.57
A-2	Nomex	18.65	0.358	0.158	58.69	44.62
A-3	Nomex	20.35	0.505	–	52.46	59.89
A-4	Nomex	20.35	0.597	–	51.86	132.59
A-5	Nomex twill	28.82	0.729	0.170	49.75	22.40
A-6	twill	28.82	0.701	0.169	51.96	37.76

TABLE IV. Transport properties of Nomex fabrics.

Sample	Fabrics properties: Structural feature	Weight, mg/cm²	Thickness, mm	Transport properties: Thermal resistance, °C/m²/W	Vapor evaporation, g/m² h	Air permeability, m³/min/m²
N-1	plain	15.26	0.438	–	67.24	170.54
N-2	plain	15.26	0.460	–	68.29	193.67
N-3	plain	15.26	0.439	–	68.85	177.58
N-4	plain	20.35	0.500	–	60.30	57.79
N-5	plain	15.26	0.465	–	66.53	197.24
N-6	plain	15.26	0.467	–	64.02	197.05
N-7	plain	15.26	0.445	0.159	72.87	188.18
N-8	plain	20.35	0.511	0.159	66.43	59.89
N-9	plain	25.43	0.597	0.164	48.84	49.10
N-10	jersey knit	22.04	0.592	–	61.11	249.03
N-11	interlock	30.52	0.968	–	56.58	300.20

fibers' chemical structure and the fabric's thickness. High thermal resistance indicates a strong barrier to metabolic body heat release generated in fire fighting, thus resulting in more heat stress and so not preferable as a uniform material. A thicker fabric will have a higher thermal resistance, as shown in Table IV. For example, for the same fiber type as Nomex, the A-2 poplin with a smaller thickness of 0.358 mm has a lower thermal resistance of 0.158 than the A-1 basket structure of 0.161 with a greater thickness of 0.554 mm. Plotting the thermal resistance of fabrics obtained from Tables III and IV versus fabric thickness results in an almost linear relationship in the range of tested Nomex fabrics (Figure 5), which confirms the accuracy of the measurements.

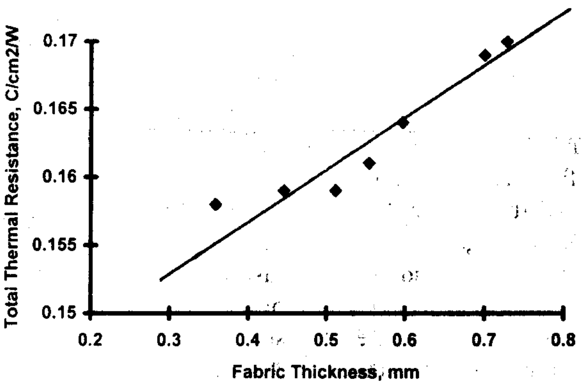

FIGURE 5. Effect of fabric thickness on total thermal resistance.

The total thermal resistance is also affected by fiber chemical compositions. For instance, C-1 and B-3 samples have a similar twill structure and thickness but are different materials. C-1, which is a cotton twill, has a higher thermal resistance, possibly because of the hollow structure of cotton fibers. Vapor evaporation of materials indicates comfort when sweating, and high vapor evaporation is preferred for such fabrics. Vapor evaporation is affected by fiber type and thickness and fabric layering. Hydrophilic samples such as cotton-containing fabrics tend to absorb moisture and hold it because of the fiber structure. Hydrophobic materials such as Nomex, polyester, and other synthetics have high wickability and can evaporate moisture quickly without wetting the materials.

Conclusions

Radiant protective performance, air permeability, vapor evaporation, and the thermal resistance of clothing are fundamentally related to the chemical and physical structures of fabrics. The results of selected fabrics, though not exclusive, indicate that radiant protective performance and transport properties are affected by the material, structure, thickness, and weight. The higher the thickness or the heavier the weight, the better the radiant protection. Radiant protective performance is not affected significantly by color in the varieties we tested. The thermal resistance of the tested fabrics varies in a relatively small range, but is associated with fabric thickness. Thick fabrics possess high thermal resistance, but the structural impacts on RPP and transport properties of fabrics are different.

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