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Thermal Protective Performance and Comfort of Wildland Firefighter Clothing: The Transport Properties of Multilayer Fabric Systems

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Abstract: A comprehensive experimental work was conducted on a series of fabric samples to examine their thermal insulation, transport, and mechanical properties, including radiant heat protection, thermal resistance, air permeability, moisture evaporation, and fabric durability. Then the properties of multilayer systems made of these fabrics are measured, and comparisons are made between the single-layer and multiple-layer systems. Also, two simple models are proposed to predict the properties of the multiple-layer systems based on the properties of the individual fabric layer. The applicability of the two models to different sets of data is also discussed.

Keywords: firefighter protective clothing, radiant protective performance, multilayer fabric system

Introduction

The performance requirements of thermal protective clothing worn by firefighters working on the scene of fires or explosions can be different depending on the heat source to which they are exposed. Although heat energy is in general transferred by conduction, convection and radiation, during a fire, the bulk of the energy causing injury on a firefighter is in the form of radiant heat [*1*]. Without flame contact, exposure to fire

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sources must be considered exclusively in terms of radiant heat, and studies of the composition of flames have found that fuel fires with flame can involve as much as 80% radiation [*2*]. Most emergency exposure situations, even when flames are present, should be considered therefore primarily in terms of radiant rather than convective heat exposure.

In a previous study by the present authors [*3*], Radiant Protective Performance (RPP), thermal resistance, air permeability, and moisture evaporation of a series of fabrics, with fiber types ranging from aramid, modacrylic, polyimide, and fire resistant cotton, were evaluated in the laboratory. The radiant protective performance of single-layer fabrics was found to be affected by the fabric structure, weight, thickness, and fiber types, which is consistent with the thermal protective performance (TPP) of fabrics previously discussed. Fabric comfort performance can be reflected by a combination of its air permeability, thermal resistance, and moisture evaporation; all of these are governed also by the same structural factors of fabrics.

A few studies about the performance of thermal protective clothing against radiant heat [*2,4-7*] have been conducted, and contributed much to what is known about the relationship of various factors like fiber type, weight and thickness and thermal protective property of the clothing. Yet, the majority of them have focused only on the single-layer of fire resistant fabric.

However, in actual fire situations exposed to high heat, a thermal protective gear assembly is not composed of a single-layer of fire resistant fabric, but often more than two layers including an outer layer and underwear.

Thermal protective property of a clothing is generally affected by the thickness, weight [*6-10*] and fiber type [*4,7*] of the fabric. If the total thickness and weight of clothing is increased by adding underwear layer beneath the outer layer, the thermal insulation will also be increased [*11*]. Baitinger and Konopasek [*12*] reported that dramatic increase in protective time was observed for multiple-layer air spaced assemblies compared with a single layer. Metha and Norman [*13*] identified that the level of protection depended on garment thickness. However, they could not establish the exact amount of protection that increased with every additional layer. Furthermore, Krasny [*14*] showed that, for multiple layers, the time to injury was always increased but with little systematic differences between the fabric types. Furthermore, it is believed also that the increase of clothing layers results in the increase of thermal protection but this performance in combination is not simply additive. Therefore, further investigation is required to determine the cumulative effect.

Thermal protection provided by a uniform and release of metabolic heat caused by wearing the uniform are two conflicting factors. That is to say, increasing the thermal insulation will reduce the ability for the uniform to transfer internal heat by adding further impedance to free evaporation of sweat at wearer's skin. Therefore, an increase in number of clothing layers, while diminishing the hazards of the fire, can also constitute an additional load on the body temperature regulatory system by impeding the exchange of heat with the surroundings and thus decreasing the wearer's working ability [*13*]. Because thermal protective and comfort properties are essential factors in thermal protective clothing but have conflicting characteristics, it is important to study the fabric combinations in multiple layers to offer optimal levels of both thermal protection and reduction of heat stress. As a result, investigating the changes of thermal protective and comfort properties of fabric combinations in multiple layers will provide useful information for design more desirable protective garments for high temperature applications [*15*]. Additionally, if a theoretical model could be established based on the measured data, the properties in multiple layers of different fabrics at the same heat exposure condition could be estimated without any experiments.

Therefore, based on the results of the single-layer fabrics, this study has investigated the changes of thermal protective and heat and moisture transfer properties due to the addition of clothing layers. Also, some simple models are applied to study the relationships between the properties of the multiple-layer systems and their constituent layers.

Materials

A total of 13 fabrics of various thickness, weight, weaves and colors, which are commonly used by wildland firefighters as uniforms and stationed clothing, were selected for this study. Several outlayer fabrics were tested both alone and then in combination with the other fabrics such as underwear fabrics. Prior to testing, all fabrics were conditioned for at least 24 hours at 21°C and 65 % RH.

In order to explore the relationship of the properties between single fabric and multiple fabric layers, the specifications of the single fabrics have been obtained and shown in Table 1.

Table 1. Specifications of the Selected Fabrics

No.	Fiber	Color	Weave	FC warp no./cm	FC fill no./cm	Thickness mm	Weight mg/cm^2
1	Cotton	white	twill	94	42	0.561	23.73
2	Nomex	yellow	plain	72	56	0.358	18.65
3	Nomex	yellow	basket	86	54	0.554	18.65
4	Firewear*	green	twill	86	44	0.523	30.52
5	Co/pet 88/12	blue	plain	52	38	0.759	30.52
6	Nomex	green	twill	75	50	0.729	28.82
7	Co/pet 88/12	white	plain	100	55	0.246	8.48
8	Cotton	white	knit	/	/	0.561	23.73
9	Cotton	blue	twill	58	45	1.013	50.85
10	Cotton	blue	plain	68	58	0.310	17.29
11	Co/pet 60/40	brown	twill	87	45	0.439	21.76
12	Cotton	white	knit	/	/	0.777	20.78

*firewear is a blend of cotton (45 %) and modacrylic (55 %)

Experimental Determination of the Fabric Transport Properties

The transport properties include those controlling the energy or gas, liquid or solid materials transferring through the fabrics. In the present study, four different properties are examined including radiant heat protection, thermal resistance, air permeability, and moisture transfer properties. The detailed introduction of the measurement of each property is provided in [*3*].

Measurement of the Fabric Radiant Protective Performance (RPP)

The apparatus for testing the thermal properties of materials under radiant heat flux was a RPP (Radiant Protective Performance) tester assembled according to the description of NFPA (National Fire Protection Association, Inc.) Standard Test 1977 (1993 Edition) [*16*].

The radiant value was determined from the graph produced by the recorder chart of the sensor response and the human tissue tolerance overlay, which was obtained by integrating the Stoll and Chianta curve with respect to time according to ASTM Standard (Thermal Protective Performance of Materials for Clothing by Open-Flame Method D 4108-87). The time in seconds was read from the overlay chart where the sensor response curve and the overlay intersect. The time in seconds was used to calculate the radiant protective performance (cal/cm^2) value for the test specimen.

Measurement of Moisture Evaporation (ME) Property

This property was measured by the amount that water vapor transports through unit area of fabrics by diffusion. After putting distilled water in a plastic container, covering the container with the specimen, and sealing tightly with a rubber band, the container and specimen were weighed before and after a given time. The water vapor transport rate (g/cm^2.hr) was then calculated as described in [*3*].

Measurement of Total Thermal Resistance (R_{ct})

Specimens were tested using the equipment specified in ASTM Standard (Thermal Transmittance of Textile Materials D1518-85). Temperature readings of the thermocouples were scanned every 30 seconds, and data were collected every 5 minutes. Once equilibrium was reached, the Total Thermal Resistance was calculated. The overall result was reported as the average of three individual specimens.

Measurement of Air Permeability (AP)

This test determines the rate of airflow through a fabric under a differential pressure between the two fabric surfaces by the calibrated orifice technique according to the ASTM Standard (Air Permeability of Textile Fabrics D 737-75). The instrument used was the Air Flow Tester, model 9025 by USTC, Inc., and the test results were reported in m^3/min/m^2, as the volume of air passing through the fabric of unit area at one minute.

Measurement of Fabric Tear Resistance (TR), Wrinkle recovery (WR) and Abrasion Resistance (AR)

Fabric durability and appearance are considered important for the firefighters uniform. The test of ASTM Standard (Abrasion Resistance of Textile Fabrics D3884-80) Rotary platform, double head method was therefore adopted to measure the abrasion resistance in terms of number of cycles to wear through a fabric. In addition, the fabric tear resistance and wrinkle recovery properties were tested according to ASTM (Tear Resistance of Woven Fabrics D1424-83) falling pendulum method using the Elmendorf tear tester, and AATCC Test (Wrinkle Recovery of Fabrics 66-1984) Recovery angle method respectively. Tests were done on both warp and weft directions, however since it was noticed that the fabrics are rather uniform in both directions, the final results were the averages of the values in the two directions.

Measurement of Weight, Thickness and Fabric Density

During the study, we found that fabric density in many cases is better correlated with fabric properties than either the fabric thickness or weight. In order to determine the fabric density, we first measured both fabric thickness according to ASTM Standard (Measuring Thickness of Textile Materials D 1777-75) at pressure 2.8 g/cm^2 using a CSI Fabric Thickness Tester, and fabric weight following ASTM Standard (Mass per Unit Area (Weight) of Woven Fabric D3776-90) using an electronic balance. The fabric density was then calculated in g/cm^3 by dividing the fabric weight by the fabric thickness.

Results and Analysis

The experimental results are provided in Table 2 for all the fabrics. As mentioned above, for any properties which involve warp and filling directions, the results are the average of the two directions. Each data point is the mean of at least 5 measurements unless specified otherwise.

Table 2. Property Measurements for the Fabrics

No	RPP cal/m^2	RPPA cal/m^2	TR kg	AP m^3/min /m^2	WR degree	ME g/m^{2}h	Density g/cm^3	AR cycles	R_{ct} ^{0}C/m^2 /W
1	8.95	9.01	4.51	47.55	91.5	45.33	0.37	139	0.171
2	7.98	7.92	4.60	53.37	129.4	58.69	0.46	303	0.158
3	8.01	8.25	>6.39	66.57	143.5	53.47	0.29	474	0.161
4	10.08	10.49	2.64	20.30	111.7	52.36	0.51	400	0.160
5	10.07	10.20	3.39	20.76	108.8	47.04	0.35	733	0.171
6	9.37	10.37	>6.39	22.40	142.6	49.75	0.35	1022	0.170
7	5.53	5.85	0.96	157.64	113.8	54.77	0.30	107	0.168
8	8.11	9.32	4.26	156.00	120.6	50.85	0.26	48	0.169
9	12.72	15.72	>6.39	18.75	107.8	45.13	0.44	3100	0.169
10	8.60	8.32	2.36	26.97	119.6	48.04	0.49	125	0.163
11	8.80	8.81	4.97	39.32	135	50.35	0.43	486	0.159
12	9.82	9.08	>6.39	112.0	98.4	48.24	0.27	72	0.175

Where RPPA is the RPP value for the same fabric but after 5 washing cycles, TR >6.39 indicates the fabric tear resistance exceeds the upper limit of the testing instrument and therefore satisfies the tear requirement.

Overall Trends

Fabric No. 9 is a cotton blue jean fabric with the highest fabric thickness and weight, it therefore possesses the greatest abrasion resistance, and RPP values both before and after washing. It also has the biggest increase in RPP values after washing due to the surface fuzz created during washing. It can be seen also that all cotton samples, i.e., 1,8,9,10,12, show high RPP values. This likely is attributable to the fact of the hollow cotton fiber structure; we have tested both a fabric with similar weight to sample 10 but made of rayon, and a cellulose fabric without hollow structure. The resulting RPP values for these two fabrics were significantly smaller.

Fabric 7 having the lowest thickness and weight, exhibited the highest air permeability among all fabrics.

Correlation Analysis between Properties

From these results, it appeared these fabric properties are interrelated. To demonstrate correlations between properties and to facilitate our analysis, we performed a correlation analysis based on the data and the results of these analyses are provided in Table 3. These results were calculated using much larger sample numbers. Since the total thermal resistance value R_{ct} was not measured in all fabrics; its correlation is not shown in the table.

Table 3. Correlation Analysis between Fabric Properties

	Weight	AP	Density	FC	ME	RPP	Thickness
Weight	1.000	-0.922**	0.948**	-0.744*	0.624	0.987**	0.967**
AP	-0.922**	1.000	-0.978**	0.457	-0.462	-0.947**	-0.815**
Density	0.948**	-0.978**	1.000	-0.541	0.437	0.946**	0.948**
FC	-0.744*	0.457	-0.541	1.000	-0.729*	-0.681*	-0.832**
ME	0.632	-0.462	0.473	-0.729*	1.000	0.664	0.624
RPP	0.987**	-0.947**	0.946**	-0.681*	0.664	1.000	0.987**
Thickness	0.967**	-0.815**	0.836**	-.832**	0.724*	0.950**	1.000

* correlation is significant at the 0.01 level.
** correlation is significant at the 0.05 level.

It can be seen from the table that the highest correlations are between RPP values and the fabric weight and thickness. RPP value also is highly correlated with fabric density. RPP value however is negatively correlated with fabric permeability, meaning that the more porous the fabric, the easier for heat flow to go through, and hence the lower in heat insulation. The air permeability on the other hand is negatively correlated with fabric density, indicating that a denser fabric will render a higher resistance to air flow. Also, the moisture evaporation is negatively correlated with fabric count (yarns/cm), which suggests that the moisture evaporation is more sensitive to the direct blockage in the path of the moisture stream.

The Transport Properties of Multilayer Fabrics

The major objective of this study is to look into the relationship of the transport properties such as the properties related to heat and fluid movement in the fabrics between single-layer and multiple-layer fabrics. For comparison, we have listed the transport properties of single-layer fabrics and multiple-layer fabrics in Tables 4 and 5 respectively.

Table 4. The Transport Properties of Single-Layer Fabrics

	RPP cal/cm^2	R_{ct} $^0C/m^2/W$	AP $m^3/min/m^2$	ME g/m^2h
1	8.95	0.171	47.55	45.33
2	7.98	0.158	53.37	58.69
3	8.01	0.161	66.57	53.47
4	10.08	0.160	20.30	52.36
5	10.07	0.171	20.76	47.04
6	9.37	0.170	22.40	49.75
7	5.53	0.168	157.64	54.77
8	8.11	0.169	156.00	50.85
9	12.72	0.169	18.75	45.13
10	8.60	0.163	26.97	48.04
11	8.80	0.159	39.32	50.35
12	9.82	0.175	112.0	48.24

In Table 5, the fabrics 3 and 2 were chosen respectively as the outlayer in combination with other fabrics to form multiple-layer systems.

First of all, let us examine the relationship in RPP values before washing. Radiant protective performance of fabrics is related to their thickness and weights, with higher RPP values corresponding to a thicker or heavier structure for the same material. As generally expected, multilayer fabrics should result in an overall RPP value equal to or higher than the addition of that of separate layers if two layers are not packed tightly. We would like to see whether the simple additive law

$$c=a+b \qquad (1)$$

will work here; where a and b are the RPP values for each single-layer and c is the value of the multilayer system.

Figure 1 shows the result where the solid line is the prediction using Equation 1, and the points are the results of experiments. Figure 1(a) and 1(b) represent the results using fabric numbers 3 and 2 as the outlayer respectively while changing the innerlayer fabrics as indicated in Tables IV and V. From the figures we can conclude that in general, every layer is important in contributing to the overall system RPP property and the overall RPP of the combinations are close to the predicted values.

Carefully examining Figure 1(a) and 1(b), we can see that majority of the data are below the prediction, especially the samples with high air permeability; one possible

Table 5. The Properties of Layered Fabrics

Layer	RPP Cal/m^2	R_{ct} $^0C/m^2/W$	AP $m^3/min/m^2$	ME g/m^2h	Thickness mm
3+8	14.59	0.194	47.37	46.83	1.115
3+12	14.99	0.204	37.58	47.64	1.028
3+4	18.97	0.188	15.54	43.92	1.077
3+1	16.88	0.189	27.25	48.04	1.115
3+5	16.42	0.203	16.92	41.71	1.313
3+9	21.06	0.206	13.72	39.70	1.567
3+11	16.50	0.186	25.24	47.14	0.993
3+10	14.64	0.184	21.49	44.42	0.864
3+4+8	20.02	0.202	15.09	32.16	1.638
3+5+7	24.12	0.210	14.90	36.88	1.559
2+8	15.78	0.185	38.59	57.09	0.919
2+12	15.91	0.197	30.72	47.14	0.832
2+4	17.58	0.184	15.27	46.83	0.881
2+1	15.04	0.184	22.49	51.66	0.919
2+5	17.33	0.194	16.00	39.60	1.117
2+9	19.43	0.206	13.99	38.89	1.371
2+11	14.40	0.183	22.40	46.23	0.797
2+10	13.56	0.178	18.65	43.82	0.668
2+4+8	23.30	0.206	14.08	33.32	1.442
2+5+7	24.03	0.210	13.90	40.10	1.363

explanation is the occurrence during the test of forced convection between multiple layers. Once heated, the air on both side of a fabric will possess different pressure gradients that in turn will initiate a forced convection between fabric layers. The air between fabric layers is no longer still, and it begins to speed up the heat energy transfer process, leading to a decrease in RPP or the thermal protection of the system. Such an impact can be observed from the sensor response curves of RPP measurements, which usually exhibit a yielding effect [*3*]. This mechanism therefore is largely controlled by the air permeability of the fabrics.

Evidence is shown in both Figure 1(a) and 1(b) that those fabrics further below the predictions are the fabrics with higher air permeability such as Fabrics 7, 8 and 12. Still, Equation 1 is found to be a good approximation even for the three layer structures in Table 5. Because RPP values of multilayer fabrics generally follow the additive law, the overall RPP always will be affected by each single-layer of the combination. Selecting fabrics with high RPP performance either can increase the RPP of the system or reduce weight or thickness of each layer of the system.

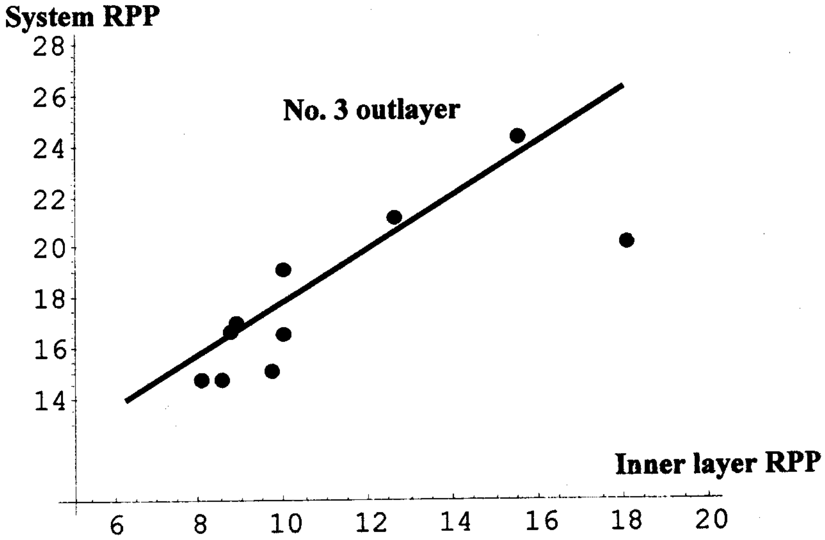

Figure 1(a) Comparison of RPP values for multiple fabric systems: Fabric No. 3 as the outlayer

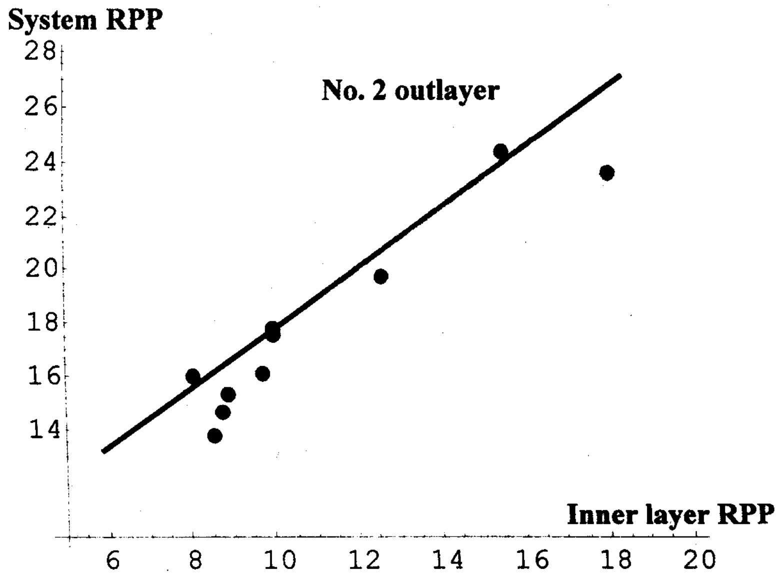

Figure 1(b) Comparison of RPP values for multiple fabric systems: Fabric No. 2 as the outlayer

We also attempted to predict the total thermal resistance R_{ct} by using Equation 1, and found the results were not correlated, meaning that the total thermal resistance is not an addition of each of the separate layers. However, the total thermal resistance of single-layer fabrics increases as the thickness of the fabrics become high. Based on such a relationship, we then plot the thermal resistance R_{ct} against the total system thickness as provided in Table 5, and results are shown in Figure 2. Since the measurement of R_{ct} was done at temperature much lower than that of the RPP test, the influence of aforementioned forced convection between multiple layers is much smaller. Therefore, a linear relationship between the R_{ct} values of the multiple-layer systems and their thickness is seen in both Figure 2(a) and (b) for both cases of different outlayer fabrics.

Next we examined the data of air permeability, and found that the inversely additive law

$$1/c=1/a + 1/b \qquad (2)$$

models the data rather well as seen in Figure 3. Because of the nature of inversely additive law, the system air permeability is controlled by the constituent fabric which has smaller air permeability. We also found that Equation 2 is not applicable to the three layer systems in Table 5.

Furthermore, we look at the data of moisture evaporation. It is obvious from the table that the simple additive law does not apply to the data. Even when we plot the data in comparison with the prediction of the inversely additive law of Equation 2 in Figure 4, no agreement is found. So we can conclude that mechanisms governing the moisture evaporation are much more complex than in other three properties that they cannot be predicted using the simple models.

Conclusions

This work confirms the previous conclusion that when dealing with the thermal insulation of fabrics, the fabric thickness and weight are the most important factors.

Similar to Nomex fabrics, cotton fabrics also show high RPP values, which is likely attributable to the fact of hollow cotton fiber structures.

Also, it is found that the simple additive law often overestimates the RPP value of a multiple-layer fabric system based on the RPP values of the individual constituent fabric layers, most likely because of the occurrence during the test of forced convection between fabric layers.

In the case of thermal resistance R_{ct}, the influence of this forced convection is negligible due to the fact that the test is done at a much lower temperature. Consequently, there exists a linear relationship between the R_{ct} values of the multiple-layer systems and their total thickness. However, the difference in R_{ct} values between different single-layer fabrics is not significant, which may indicate that fiber type and fabric weave have less impact on R_{ct} value than layering.

It also is found that the inversely additive law is applicable to the prediction of fabric permeability of multiple-layer system very nicely. However, for fabric moisture

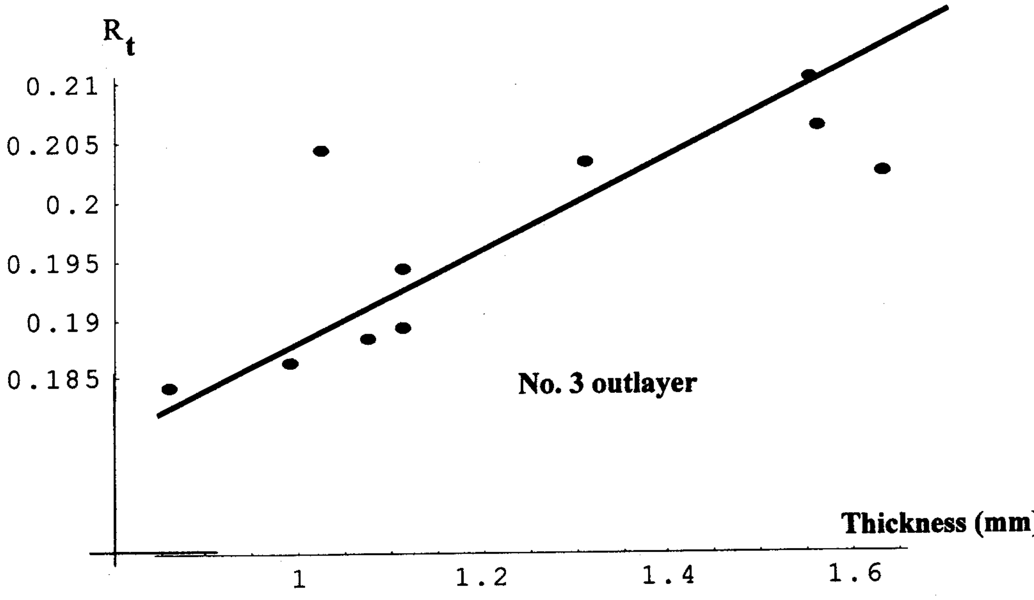

Figure 2(a) Comparison of thermal resistance values for multiple fabric systems: Fabric No.3 as the outlayer

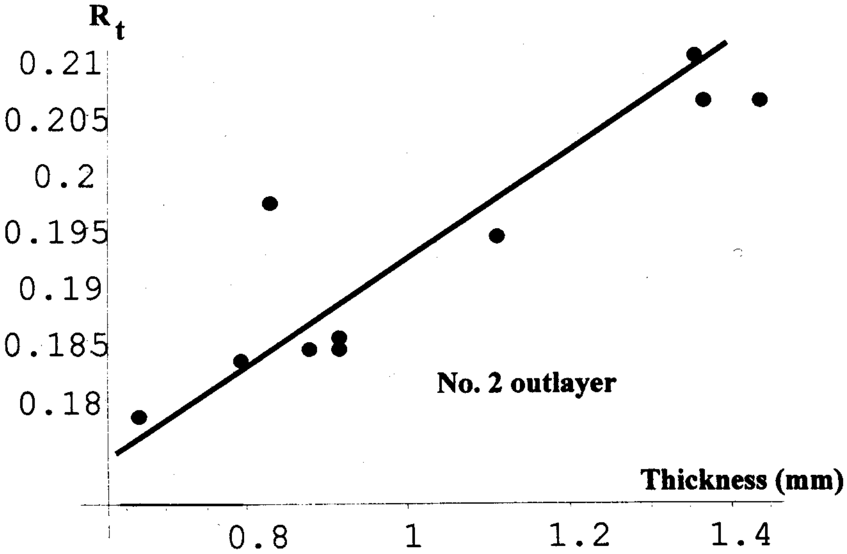

Figure 2(b) Comparison of thermal resistance values for multiple fabric systems Fabric No.2 as the outlayer

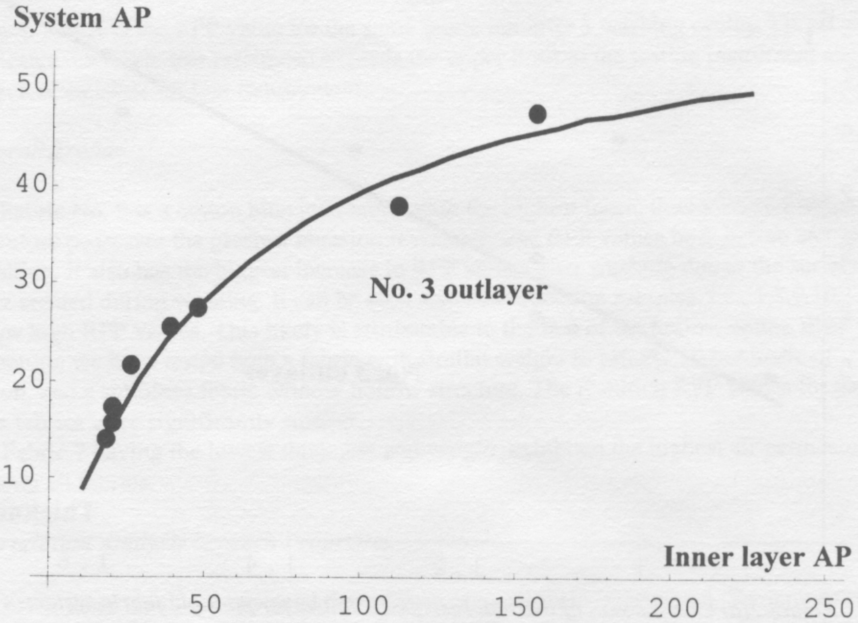

Figure 3(a) Comparison of air permeability values for multiple fabric systems Fabric No. 3 as the outlayer

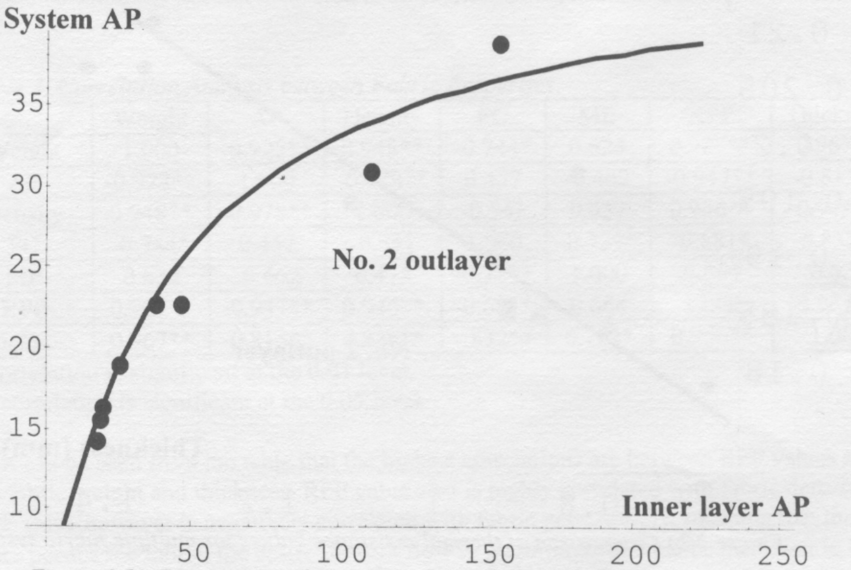

Figure 3(b) Comparison of air permeability values for multiple fabric systems Fabric No. 2 as the outlayer

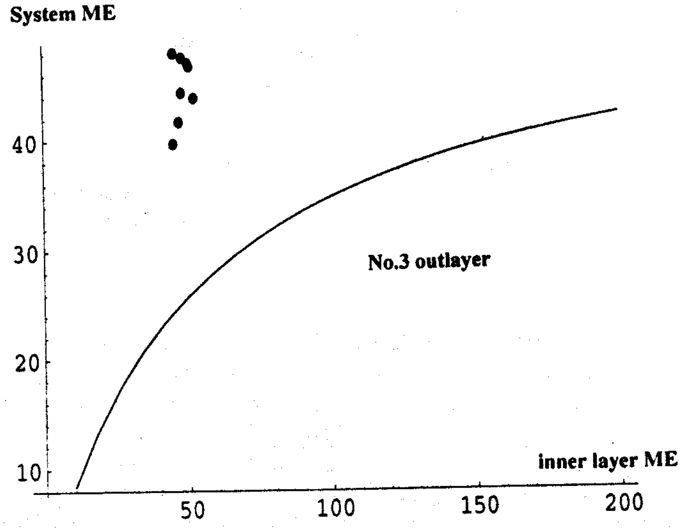

Figure 4 (a) Comparison of moisture evaporation for multiple layer fabric system: Fabric No. 3 as the outlayer

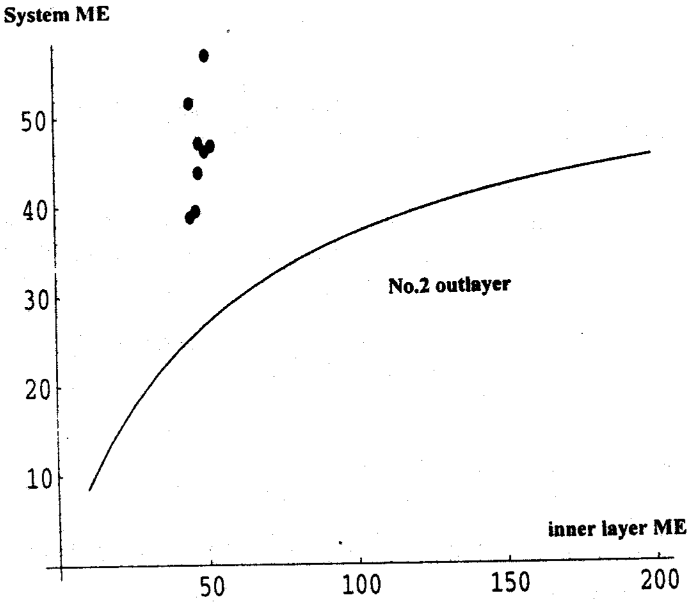

Figure 4 (b) Comparison of moisture evaporation for multiple layer fabric system: Fabric No. 2 as the outlayer evaporation, more complex mechanisms are involved so that more sophisticated models are needed to predict the property for multiple-layer fabric systems.

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