A Report

to

F.I.E.R.O

on

Total Heat Loss and Evaporative Resistance Measurements of Eight Firefighter Composites

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from

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Eight composites samples were submitted, by F.I.E.R.O, to the Textile Protection and Comfort Center (TPACC) in the College of Textiles at North Carolina State University, for characterization of the heat and moisture transport properties that contribute to thermal strain. These eight samples represent composites used in the construction of test garments that were subjected to a physiological manikin study that is the subject of Report #PSM170626 Phase II Testing: Predicted Physiological Responses from Eight Firefighting Suits Tested in Three Environmental Conditions, which was also sponsored by F.I.E.R.O. The purpose of this report is to describe the test method used to characterize these materials and to present the results of the laboratory test.

Test Material

Rolls of fabrics were sent by the customer. These fabrics were cut and assembled into eight sets of composites (three reps each) based on information provided by the customer. Each composite was identified by one of the following labels **G1, G2, G3, G4, G5, G6, G7,** or **G8**. A generic listing of the layers within each composite is detailed in Appendix A.

It should be noted that **G1, G2, G3, G4, G5** and **G6** are made of materials that are compliant with NFPA 1971. Samples **G7** and **G8** would not be compliant as they contain an impermeable membrane (**G7**) or no membrane at all (**G8**).

Test Method

The heat and moisture transfer properties determined in this testing were calculated from measurements of thermal transport made with the Thermetrics sweating guarded hot plate. Samples were tested in accordance with the procedures of ISO 11092 Measurement of thermal and water vapour resistance under steady-state conditions (sweating guarded-hotplate test) and the ASTM F 1868, Standard Test Method for Thermal and Evaporative Resistance of Clothing Materials Using a Sweating Hot Plate, Part C. ISO 11092 was used to measure the evaporative resistance and ASTM F1868 Part C was used to measure the total heat loss. A description of the measured heat transfer parameters is given below; other details pertaining to instrumentation, methods and calculations are given in Appendix B.

Dry and Sweating Hot Plate Tests

The measurement of heat transfer is a measure of heat flow from the calibrated test plate (heated to a surface temperature of 35°C) through the composite into the test environment. For evaporative resistance measurements the test environment is set to 35°C, 40%RH. This condition removes the ability for heat to flow through conduction and focuses on how the fabric allows moisture to evaporate from the surface of the test plate.

For the total heat loss measurement the environmental conditions are set to 25°C, 65%RH, and measurements are taken with both dry and wet plate conditions. Measurements from these conditions are used to measure the thermal resistance, apparent evaporative resistance and the total heat loss from a fabric.

Measurements reported for these experiments are defined below

a. **Apparatus Evaporative Resistance (R_{et0})**, [(ΔPa)(m^2)/W], the resistance to evaporative heat transfer provided by the liquid barrier and surface air layer as measured on the bare plate (with liquid barrier attached).

b. **Evaporative Resistance of the Textile (R_{et})**, [(ΔPa)(m^2)/W], the resistance to evaporative heat transfer provided by the textile system alone.

d. **Total Thermal Resistance (R_{ct})**, [(Δ°C)(m^2)/W], the total resistance to dry heat transfer (insulation) for a fabric system including the surface air layer.

e. **Intrinsic Thermal Resistance (R_{cf})**, [(Δ°C)(m^2)/W], the resistance to dry heat transfer provided by the fabric system alone.

f. **Bare Plate Thermal Resistance (R_{cbp})**, [(Δ°C)(m^2)/W], the resistance to dry heat provided by the surface air layer as measured on the bare plate.

g. **Apparent Total Evaporative Resistance (R_{et}^A)**, [(ΔkPa)(m^2)/W], the total resistance to evaporative heat transfer for a fabric system including the surface air layer and liquid barrier (the descriptor term 'apparent' is added to account for the fact that heat transfer may have an added condensation component in non-isothermal conditions).

h. **Apparent Intrinsic Evaporative Resistance (R_{ef}^A)**, [(ΔkPa)(m^2)/W], the resistance to evaporative heat transfer provided by the fabric system alone.

i. **Bare Plate Evaporative Resistance (R_{ebp})**, [(ΔkPa)(m^2)/W], the resistance to evaporative heat transfer provided by the liquid barrier and surface air layer as measured on the bare plate (with liquid barrier attached).

j. **Total Heat Loss (Q_t)**, [W/m^2], an indicator of the heat transferred through the test material by the combined dry and evaporative heat loss, from a fully sweating test plate surface into the test environment. Total heat loss, measured at a 100% wet skin condition, indicates the highest predicted metabolic activity level that a wearer may sustain and still maintain body thermal comfort while in a highly stressed state in the test environment. Note, however, that the sweating hot plate does not consider effects such as insulating air layers, garment design, and fit. Thus, the Total Heat Loss value obtained represents the highest theoretically possible amount of heat that can be transferred through a material system in a 25°C, 65%RH condition without active cooling or ventilation.

Weight and Thickness

Weight is measured according to ASTM D 3776 small swatch option. Three specimens (20 x 20 inch) were weighed on an analytical balance and the weight was calculated in mass per unit area (oz/yd^2). Thickness is measured according to ASTM D 1777 test option 1. Three specimens (20 x 20 inch) were measured with a thickness gauge (mm) at an applied pressure of 0.6 psi at various locations of the fabric.

Test Results

The average values for the Evaporative Resistance of the textile (R_{et}), and The Total Heat Loss (Q_t) of the sample tested are contained in Table 1. Weights and thicknesses are given in Table 2. Individual results and detailed data of each test sample are displayed in Appendix C.

Table 1: Sample Results from Sweating Hot Plate

Sample	R_{et}	Q_t
G1	**31.4**	**273.0**
G2	**26.9**	**254.6**
G3	**23.4**	**307.8**
G4	**21.8**	**256.8**
G5	**27.8**	**241.5**
G6	**27.6**	**246.5**
G7	**396***	**101.9**
G8	**13.7**	**272.8**

*The values reported for G7 were obtained while testing at an ambient temperature of 33°C which was deemed impermeable due to near zero power being required in order to maintain the plate temperature of 35°C at an ambient temperature of 35°C. This temperature reduction was necessary in order to obtain an actual value.

Table 2: Average Weights and Thicknesses

Sample	Weight (oz/yd^2)	Thickness (mm)
G1	**19.89**	**2.59**
G2	**20.07**	**3.20**
G3	**20.35**	**2.23**
G4	**21.45**	**2.28**
G5	**19.68**	**2.15**
G6	**20.22**	**2.12**
G7	**25.70**	**2.92**
G8	**18.30**	**2.68**

Caveat

These data, obtained under controlled laboratory conditions, characterize the thermal resistance values of test sample responses to specific environmental conditions. These results should not be used to appraise the safety benefits or risks of the materials, products, or assemblies in extreme use conditions. The relationships between laboratory tests and field performance are not simple, and many things must be considered when making practical translations. Clothing comfort and heat stress performance are determined by many factors including material properties, garment design and fit, activity level, and the environmental conditions of use. These results do not address the full range of these issues. It is not our intention to recommend, exclude, or predict the suitability of any commercial product for a particular end use.

Appendix A: Composite Layer Information

G1	
Outer shell	7.5 oz/yd^2 plain weave (93% Nomex®/5% Kevlar®/2% anti-static blend spun yarn)
Moisture Barrier	4.6 oz/yd^2 (bicomponent ePTFE laminated to a Nomex® spunlace)
Thermal liner	7.1 oz/yd^2 (2 layers of Basofil®-/Aramid blend spunlaced quilted to Nomex® spun yarn, calendared plain weave fabric)

G2	
Outer shell	7.5 oz/yd^2 plain weave (93% Nomex®/5% Kevlar®/2% anti-static blend spun yarn)
Moisture Barrier	5.2 oz/yd^2 (bicomponent ePTFE laminated to Nomex® spunlace)
Thermal liner	7.2 oz/yd^2 (single layer of aramid fiber needle punched fabric quilted to 100% Nomex® spun fiber, plain weave fabric)

G3	
Outer shell	7.5 oz/yd^2 plain weave (93% Nomex®/5% Kevlar®/2% anti-static blend spun yarn)
Moisture Barrier	5.2 oz/yd^2 (bicomponent ePTFE laminated to 80% Nomex IIIA / 20% PBI woven pajama-check)
Thermal liner	7.2 oz/yd^2 (two layers of Nomex® spunlaced fabrics [1.5 and 2.3 oz/yd^2] quilted to 100% Nomex® spun fiber, plain weave fabric)

G4	
Outer shell	7.0 oz/yd^2 twill weave (70**%** PBI/Kevlar® spun yarns and 30% Kevlar filament yarns)
Moisture barrier & Thermal liner system	98% NOMEX®/2% anti-static spun yarn woven fabric, plain weave, laminated to an ePTFE film
	Kevlar®/Nomex® blend patterned nonwoven spunlace with scrim, laminated to an ePTFE film
	60% Kevlar® filament yarn / 40% Nomex®/ Lenzing®FR blend spun yarn, twill weave, coupled with an ePTFE film

G5	
Outer shell	7.0 oz/yd^2 twill weave (70**%** PBI/Kevlar® spun yarns and 30% Kevlar filament yarns)
Moisture Barrier	4.7 oz/yd^2 (bicomponent ePTFE laminated to 100% Nomex® woven pajama-check)
Thermal liner	6.8 oz/yd^2 (two layers of 80% Aramid 20% PBI apertured spunlaced fabrics [1.4 and 1.8 oz/yd^2] quilted to 60% Kevlar®, 26% Nomex®, 14% Lenzing FR, twill weave fabric)

G6	
Outer shell	7.0 oz/yd^2 twill weave (70**%** PBI/Kevlar® spun yarns and 30% Kevlar filament yarns)
Moisture Barrier	5.2 oz/yd^2 (bicomponent ePTFE laminated to 80% Nomex IIIA / 20% PBI woven pajama-check)
Thermal liner	6.8 oz/yd^2 (two layers of 80% Aramid 20% PBI apertured spunlaced fabrics [1.4 and 1.8 oz/yd^2] quilted to 60% Kevlar®, 26% Nomex®, 14% Lenzing FR, twill weave fabric)

G7	
Outer shell	7.75 oz/yd^2 Twill with rip stop (Blend of Kevlar® and Basofil® fibers)
Moisture Barrier	9 oz/yd^2 (Neoprene laminated to a poly cotton cloth)
Thermal liner	9.25 oz/yd^2 (single layer of recycled Nomex quilt, quilted to Nomex® spun fiber, plain weave fabric)

G8	
Outer shell	5.3 oz/yd^2 ripstop (Blend of Technora® and PBO spun yarns)
Moisture Barrier	4.5oz/yd^2 100% Nomex® pajama-check
Thermal liner	7.6oz/yd$^{2(}$ single layer of 50% Nomex® 50% Kevlar® needle-punched quilted to a 68% Kevlar®, 26% FR Viscose, 11% Polyamide ring spun fabric)

Appendix B: Instrument, Methods, and the Calculation of Total Heat Loss Parameters

Heat Transfer With/Without Moisture (Sweating Skin Condition)

Heat transfer makes it possible to predict the body heat that will flow from the skin surface through the material into the surrounding atmosphere. Heat and moisture transfer properties are key properties affecting clothing comfort. These thermal properties are analyzed using a guarded sweating hotplate system from Measurement Technology Northwest Inc. housed in an environmental test chamber set to achieve the required ambient conditions.

Tests were run in accordance with requirements of ISO 11092 Measurement of thermal and water vapour resistance under steady-state conditions (sweating guarded-hotplate test) and ASTM F 1868 Standard Test Method for Thermal and Evaporative Resistance of clothing Materials Using a Sweating Hot Plate; Part C. The specifics and allowable refinements are as follows:

- For a given replicate the temperatures, humidity, voltage and current are logged at 2 minute intervals with an acceptable steady-state deviation of no more than 1.5% for at least 30 minutes.
- Wind speed is set to 1 m/s with a turbulence value of ~0.07.
- Using system constants, R_{et}, R_{cf}, R_{ef}^{A}, and Q_t are calculated for each replicate. The replicate values are averaged to provide overall sample averages as reported in this document.

Calculation of Evaporative Resistance

R_{et} = evaporative resistance of the textile specimen

$$R_{et} = \{(P_S - P_a)\cdot A/(H - H_c)\} - R_{et0}$$

where:

P_S = water vapor pressure at the plate surface (Pa),
P_a = water vapor pressure in the local environment (Pa),
A = area of the test plate (0.01 m^2),
H = power input (W),
H_c = Power correction factor (Set to 0 for modern plates. Correction is need for older plates with poor guard sections)
R_{et0} = resistance to evaporative heat transfer provided by the liquid barrier and surface air layer of the plate

Calculation of Total Heat Loss Parameters

Calculation of the Total Heat Loss, Q_t [W/m^2], requires measurements from both dry and sweating conditions on a hotplate. Each total heat loss calculation was derived from the average of three test replications. Total heat loss, Q_t, was calculated using the following formula:

$$Q_t = \frac{10°C}{R_{cf} + .04} + \frac{3.57\ kPa}{R_{et}^A + .0035}$$

where:

Q_t = Total Heat Loss (THL),

R_{cf} = the average intrinsic thermal resistance of the sample alone and is determined by subtracting the average dry bare plate resistance (R_{cbp}) from the average of the total thermal resistance (R_{ct}) of the specimens tested,

R_{ef}^A = Average apparent intrinsic evaporative resistance of the sample alone as determined by the apparent total evaporative resistance (R_{et}^A) minus the average bare plate evaporative resistance (R_{ebp}),

R_{ct} = total thermal resistance of the specimen and surface air layer defined as

$$R_{ct} = \frac{(T_s - T_a) \cdot A}{H}$$

where:

T_s = Temperature of the plate surface (35°C),
T_a = Temperature in the local environment (25°C),
A = area of the test plate (0.01 m^2), and
H = power input (W),

R_{et}^A = apparent total evaporative resistance of the specimen and surface air layer defined as

$$R_{et}^A = \frac{(P_s - P_a) \cdot A/H - (T_s - T_a) \cdot A}{R_{ct}}$$

where:

P_s = water vapor pressure at the surface plate (kPa),
P_a= water vapor pressure in the local environment (kPa),
A = area of the test plate (0.01 m^2),
H = power input (W),
T_s = temperature at the plate surface (35°C),
T_a = temperature at the local environment (25°C), and
R_{ct} = total thermal resistance of the specimen and surface air layer [(Δ°C)(m^2)/W].

Appendix C: NCSU Sweating Thermal Hot Plate Results

Sample – G1

Rep	R_{et}	R_{ct}	R_{et}^{A}	R_{cf}	R_{ef}^{A}	Q_t
1	33.07	0.2005	0.01855	0.125	0.01287	278.87
2	31.10	0.1957	0.01877	0.120	0.01308	277.89
3	30.05	0.1906	0.02024	0.115	0.01456	262.36
AVG	**31.41**	**0.196**	**0.01919**	**0.120**	**0.01350**	**273.04**

Weight

Rep	Weight (oz/yd^2)
1	19.95
2	19.91
3	19.79
Average	**19.89**

Thickness

Rep	Thickness (mm)
1	2.54
2	2.60
3	2.62
4	2.60
5	2.56
6	2.58
7	2.60
8	2.62
9	2.60
Average	**2.59**

Sample – G2

Rep	R_{et}	R_{ct}	R_{et}^{A}	R_{cf}	R_{ef}^{A}	Q_t
1	26.60	0.2118	0.02155	0.136	0.01587	241.23
2	27.05	0.2095	0.01954	0.134	0.01386	263.29
3	26.92	0.203	0.02008	0.127	0.01440	259.37
AVG	**26.86**	**0.208**	**0.02039**	**0.132**	**0.01471**	**254.63**

Weight

Rep	Weight (oz/yd^2)
1	20.14
2	20.01
3	20.06
Average	**20.07**

Thickness

Rep	Thickness (mm)
1	3.26
2	3.20
3	3.24
4	3.28
5	3.24
6	3.18
7	3.22
8	3.04
9	3.12
Average	**3.20**

Sample – G3

Rep	R_{et}	R_{ct}	$R_{et}{}^{A}$	R_{cf}	$R_{ef}{}^{A}$	Q_t
1	22.89	0.1562	0.01788	0.080	0.01220	310.66
2	23.57	0.1587	0.01793	0.083	0.01225	308.17
3	23.60	0.1586	0.01819	0.083	0.01250	304.65
AVG	**23.35**	**0.158**	**0.01800**	**0.082**	**0.01232**	**307.82**

Weight

Rep	Weight (oz/yd^2)
1	20.34
2	20.31
3	20.40
Average	**20.35**

Thickness

Rep	Thickness (mm)
1	2.24
2	2.26
3	2.24
4	2.18
5	2.24
6	2.22
7	2.28
8	2.20
9	2.18
Average	**2.23**

Sample – G4

Rep	R_{et}	R_{ct}	R_{et}^A	R_{cf}	R_{ef}^A	Q_t
1	22.59	0.1511	0.02275	0.075	0.01707	260.43
2	20.16	0.1595	0.02281	0.084	0.01712	254.09
3	22.71	0.1525	0.02317	0.077	0.01748	255.97
AVG	**21.82**	**0.154**	**0.02291**	**0.078**	**0.01723**	**256.83**

Weight

Rep	Weight (oz/yd^2)
1	21.38
2	21.52
3	21.45
Average	**21.45**

Thickness

Rep	Thickness (mm)
1	2.28
2	2.32
3	2.30
4	2.22
5	2.22
6	2.24
7	2.28
8	2.30
9	2.32
Average	**2.28**

Sample – G5

Rep	R_{et}	R_{ct}	R_{et}^{A}	R_{cf}	R_{ef}^{A}	Q_t
1	28.38	0.1807	0.02292	0.105	0.01724	241.28
2	27.25	0.1752	0.02300	0.099	0.01732	243.32
3	27.64	0.1751	0.02343	0.099	0.01775	239.90
AVG	**27.76**	**0.177**	**0.02312**	**0.101**	**0.01743**	**241.50**

Weight

Rep	Weight (oz/yd^2)
1	19.79
2	19.54
3	19.70
Average	**19.68**

Thickness

Rep	Thickness (mm)
1	2.12
2	2.14
3	2.16
4	2.18
5	2.16
6	2.10
7	2.18
8	2.16
9	2.18
Average	**2.15**

Sample – G6

Rep	R_{et}	R_{ct}	R_{et}^{A}	R_{cf}	R_{ef}^{A}	Q_t
1	26.74	0.1849	0.02348	0.109	0.01779	234.83
2	28.27	0.1714	0.02210	0.095	0.01642	253.11
3	27.71	0.1731	0.02217	0.097	0.01649	251.56
AVG	**27.57**	**0.176**	**0.02258**	**0.100**	**0.01690**	**246.50**

Weight

Rep	Weight (oz/yd^2)
1	20.24
2	20.14
3	20.28
Average	**20.22**

Thickness

Rep	Thickness (mm)
1	2.04
2	2.12
3	2.16
4	2.08
5	2.10
6	2.12
7	2.16
8	2.16
9	2.14
Average	**2.12**

Sample – G7

Rep	R_{et}	R_{ct}	R_{et}^{A}	R_{cf}	R_{ef}^{A}	Q_t
1	394.68	0.2079	0.07759	0.132	0.07190	105.52
2	396.70	0.2207	0.08254	0.145	0.07685	98.57
3	396.56	0.2179	0.07848	0.142	0.07279	101.77
AVG	**395.98**	**0.216**	**0.07953**	**0.140**	**0.07385**	**101.95**

Weight

Rep	Weight (oz/yd^2)
1	25.63
2	25.71
3	25.75
Average	**25.70**

Thickness

Rep	Thickness (mm)
1	2.94
2	2.90
3	2.84
4	2.98
5	3.00
6	2.92
7	2.82
8	2.98
9	2.92
Average	**2.92**

Sample – G8

Rep	R_{et}	R_{ct}	R_{et}^A	R_{cf}	R_{ef}^A	Q_t
1	13.99	0.1856	0.01929	0.110	0.01360	275.58
2	14.04	0.1904	0.02053	0.114	0.01484	259.40
3	13.15	0.1778	0.01895	0.102	0.01327	283.44
AVG	**13.72**	**0.185**	**0.01959**	**0.109**	**0.01390**	**272.81**

Weight

Rep	Weight (oz/yd^2)
1	18.66
2	18.09
3	18.16
Average	**18.30**

Thickness

Rep	Thickness (mm)
1	2.76
2	2.58
3	2.56
4	2.76
5	2.80
6	2.60
7	2.76
8	2.78
9	2.56
Average	**2.68**