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Estimates of Thermal Conductivity for Unconditioned and Conditioned Materials Used in Fire Fighters' Protective Clothing

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By

Robert Vettori

Abstract

Fire fighters' protective clothing provides a limited amount of thermal protection from environmental exposures produced by fires. This level of thermal protection varies with the design, materials, construction, and fit of the protective garments. Limits of thermal protection may be analyzed using the thermophysical properties of garment materials. However, little information is currently available for analyzing and predicting protective garment thermal performance. To address this need, a research effort was begun to measure the thermal properties of fire fighters' protective clothing materials. This report presents thermal conductivity data for ten materials used in fabricating fire fighters' protective clothing. These materials included: (a) outer shell fabrics, (b) moisture barriers, and (c) thermal liner battings. The thermal conductivity data for each material was obtained twice. Once when the material was new and once after the material had undergone a conditioning process of five washings and dryings by a contract cleaner that specializes in cleaning, decontaminating and repair of fire fighters' protective clothing. The thermal conductivity of individual protective clothing materials was measured using the test procedure specified in ASTM C 518 Standard Test Method for Steady-State Thermal Transmission Properties by Means of Heat Flow Meter Apparatus. Measurements producing estimates of thermal conductivity for a single layer of materials were carried out at mean test temperatures of 20 °C (68 °F), 48 °C (118 °F), 55 °C (131 °F), and 72 °C (162 °F). No visible physical changes were observed with any of the materials tested at these temperatures. For unconditioned materials, the thermal conductivity estimates ranged from 0.034 W/m K to 0.093 W/m K. For the conditioned materials the thermal conductivity estimates ranged from 0.033 W/m K to 0.089 W/m K. Thermal conductivity values increased for all materials as mean test temperatures were increased.

Key words: fires, fire fighters, heat transfer, protective clothing, test method, thermal analysis, thermal conductivity,

1 Introduction

The thermal performance of fire fighters' protective clothing is primarily based on the thermophysical properties of the materials used to construct the clothing. Analysis and prediction of protective clothing thermal performance requires the use of numerical parameters for thermophysical properties for all materials used in garment construction. Currently, little information is available for making detailed studies of protective clothing thermal performance. The physical properties used for thermal analysis and predictions are: (a) thermal conductivity; (b) specific heat; (c) density; and (d) the thermal spectral properties of emissivity, transmissivity, and reflectivity [1]. This paper discusses measurements of thermal conductivity. Data collected on the emissivity, transmissivity, and reflectivity of materials will be described in a separate report [2].

This study builds upon the work performed by Lawson and Pinder [3]. They give estimates for the thermal conductivity of 10 different materials used in the construction of fire fighters' protective clothing. All measurements taken by Lawson and Pinder were on new or unused material as delivered by the manufacturer. In this study, four of the materials used by Lawson and Pinder and six additional materials are investigated.

Estimates of thermal conductivity for the six additional materials were determined. Then the six new materials and the four materials from Lawson and Pinder were conditioned by undergoing a process of five washings and dryings by a contract cleaner that specializes in cleaning, decontaminating and repair of fire fighters' protective clothing. Many of the test methods used for the certification of fire fighters' protective clothing by The National Fire Protection Association (NFPA) 1971 Standard on Protective Ensemble for Structural Fire Fighting [4] require that the material pass the test method when new and after undergoing the conditioning process of five washings and dryings.

Thermal conductivity of a material relates to the rate of heat transfer through the material. Heat transfer by this mechanism is based on the transfer of energy of motion between adjacent molecules. This property will vary with the amount of heat energy that a material is exposed to and is therefore moderately temperature dependent.

Thermal conductivity will change for materials as the thermal exposure changes. This study has developed estimates of thermal conductivity for protective clothing materials over a range of temperatures below where visible physical changes occur. Observed physical changes in materials would indicate that the materials are beginning to degrade. As a result, the steady state measurement of the materials would be compromised. Testing was carried out at the following temperatures: 20 °C (68 °F), 48 °C (118 °F), 55 °C (131 °F), and 72 °C (162 °F).

2 Test Apparatus

Thermal conductivity measurements were made using a commercially manufactured test apparatus. The apparatus used was a Holometrix, Rapid-k, Model VT400-A[1] with computer

[1] Certain commercial equipment, instruments, or materials are identified in this paper in order to adequately specify the experimental procedure. Such identification does not imply recommendation or endorsement by the National Institute of Standards and Technology, nor does it imply that the materials or equipment identified are necessarily the best available for the purpose.

control and data logging. This test equipment was operated in accordance with ASTM C 518, Standard Test Method for Steady-State Thermal Transmission Properties by Means of Heat Flow Meter Apparatus [5].

The ASTM C 518 standard is a comparative method for measuring thermal conductivity that is based on apparatus calibrations obtained from a Standard Reference Material. The heat flow meter apparatus establishes a steady state one-dimensional heat flux through the test specimen that is located between two parallel plates that are controlled at constant but different temperatures. Fourier's law of heat conduction, Equation 1, is used to calculate thermal conductivity. Computer software used for calculating thermal conductivity is based on ASTM C 1045, Practice for Calculating Thermal Transmission Properties for Steady State Conditions [6].

Figure 1 shows the principle of the apparatus operation. A specimen is placed in the test chamber between the two plates. The plates attain different, but constant temperatures. Since there is a temperature difference across the specimen, heat flows through the specimen from the hotter to the cooler plate. When the apparatus reaches thermal equilibrium, the temperature of each plate, the temperature gradient across the specimen, and the heat flow through the specimen are constant. At thermal equilibrium, thermal conductivity can be measured.

The heat flow across the specimen is given by:

$$q = \lambda A \frac{\Delta T}{\Delta X} \qquad \text{Equation 1}$$

where $q =$ heat flow W

$\lambda =$ thermal conductivity of the specimen $W/m\,K$

$A =$ area through which the heat flows m^2

$\Delta T =$ temperature difference across the specimen K

$\Delta X =$ thickness of the specimen m

The heat flow transducer measures the heat flow through the specimen. The signal of the heat flow transducer is a voltage which is proportional to the heat flow through the transducer. In the apparatus, the area of the heat flow transducer represents the area through which the heat flows to the transducer and is the same for all specimens. Equation 1 can be re-written in the following form:

$$\frac{\lambda}{\Delta X} = N \frac{V}{\Delta T} \qquad \text{Equation 2}$$

where V = the transducer voltage V

N = the calibration factor that relates the voltage signal of the heat flow transducer to the heat flux through the specimen. W/m^2V

The apparatus was calibrated using NIST Standard Reference Material (SRM) 1450c, a fibrous glass board insulation [7]. This SRM measured 305 mm x 305 mm (12 in x 12 in) and 24.7 mm (0.972 in) thick. The SRM density was 158.09 kg/m^3 (9.87 lb/ft^3). The primary thermal conductivity calibration for the SRM at 24 °C (75 °F) was 0.0334 W/m K. Figure 2 shows a temperature calibration plot for SRM 1450c over the range from 10 °C (50 °F) to 80 °C (194 °F). These data show that the SRM's thermal conductivity has a linear relationship over the temperature calibration range and the range of temperatures used for testing the fire fighter protective clothing materials.

3 Materials

Ten different materials were tested in this study, see Table 1 below. All of these materials are currently used as components of fire fighters' protective clothing. Of the materials tested, three were moisture barriers, four were outer shell fabrics, and three were thermal liners. Even though this group of materials does not cover all of the materials currently used to fabricate fire fighters' protective clothing, it does represent a significant fraction of the materials presently in use. All materials used were received from the manufacturer rolled as bolts on thick walled paper tubes.

Table 1 List of test materials

Material*	Use
Three Layer AraFlo® with Chambry Face Cloth	Thermal Liner
Two Layer AraFlo® with Glide™ Face Cloth	Thermal Liner
Aralite®	Thermal Liner
Black Fusion™	Outer Shell
Black Basofil® Kevlar®	Outer Shell
PBI® Kevlar® Kombat™	Outer Shell
Nomex® III Defender™	Outer Shell
Crosstech® on Nomex®	Moisture Barrier
PTFE on non woven Nomex®	Moisture Barrier
Nomex® IIIA Pajama Check	Moisture Barrier

* AraFlo® is a registered trademark of Lion Apparel, Inc.
Glide™ and Fusion™ are trademarks of Safety Components Fabric Technologies, Inc.
Aralite® is a registered trademark of Southern Mills.
Kombat™ and Defender™ are trademarks of Southern Mills.
Basofil® is a registered trademark of Basofil Fibers, LLC.
Kevlar® and Nomex® are registered trademarks of E. I. Dupont.
Crosstech® is a registered trademark of W. L. Gore and Associates.
PBI® is a registered trademark of the Celanese Corporation.

Aralite, PBI Kevlar Kombat, Nomex III Defender, and Nomex IIIA Pajama Check were the four materials that were also included in the Lawson and Pinder study.

3.1 Test Specimens

Test specimens were cut from the rolls of materials received from the manufacturers. The Rapid-k test apparatus requires that specimens measure 305 mm x 305 mm (12 in x 12 in). Specimen outlines were marked on the materials using a felt tipped ink pen, and then each specimen was cut from the roll using scissors. Specimens were cut from each material and were stacked until they reached a height of 25 mm (1 in). The number of cut specimens varied between different materials based on the material's thickness. After all specimens were cut, three specimens were randomly selected from each set of materials. The specimen's dimensions were measured using a ruler for large dimensions and a micrometer for thickness. There was a minimum of twelve measurements made for each specimen dimension. Average dimensions were then calculated. In addition, each specimen was weighed using a laboratory balance to determine its mass. The density for each material was calculated using the collected data. See the results in Table 2 below. Thermal conductivity measurements were then performed on the test specimens using the test apparatus as described in Section 4 below. These test specimens were then conditioned by undergoing a process of five washings and dryings by a contract cleaner that specializes in cleaning, decontaminating and repair of fire fighter protective clothing. After this conditioning process, the test specimens were again measured and weighed and the density calculated. The results of these measurements on the conditioned test specimens are also in Table 2 below.

Table 2 Unconditioned and conditioned test specimen dimensions and densities.

Material	Use	Unconditioned (New)		Conditioned (Washed)	
		Thickness (m)	Density (kg/m^3)	Thickness (m)	Density (kg/m^3)
Three Layer AraFlo® with Chambry Face Cloth	Thermal liner	0.00312	89	0.00353	80
Two Layer AraFlo® with Glide™ Face Cloth	Thermal liner	0.00223	121	0.00249	103
Aralite®	Thermal liner	0.00359	74	0.00368	70
Black Fusion™	Outer shell	0.00069	344	0.00082	293
Black Basofil® Kevlar®	Outer shell	0.00077	352	0.00083	324
PBI® Kevlar® Kombat™	Outer shell	0.00080	322	0.00079	315
Nomex® III Defender™	Outer shell	0.00082	317	0.00082	307
Crosstech® on Nomex®	Moisture Barrier	0.00050	335	0.00055	299
PTFE on non woven Nomex®	Moisture Barrier	0.00114	134	0.00126	117
Nomex® IIIA Pajama Check	Moisture Barrier	0.00052	317	0.00052	300

4 Experimental Procedure

Thermal conductivity for each of the materials was measured at four different temperatures, 20 °C (68 °F), 48 °C (118 °F), 55 °C (131 °F), and 72 °C (162 °F). These temperatures were selected from ASTM C 1055, Standard Guide for Heated Systems Surface Conditions That Produce Contact Burn Injuries [8], and cover the range of temperatures that produce burn injuries. The 20 °C (68 °F) temperature represents room temperature, 48 °C (118 °F) represents a human tissue temperature at which a first degree burn occurs, 55 °C (131 °F) is the human tissue temperature that is likely to cause a second degree burn [9], and 72 °C (162 °F) is the human tissue temperature at which an instantaneous burn injury is likely to occur. These four temperatures resulted in different temperature settings for each of the heat flow meter plates. The mean temperature for each of the test conditions was established by adjusting the thermally controlled apparatus plates so there would be a temperature difference of 15 °C (27 °F) between the plates. Apparatus plate temperature settings for each of the mean test temperatures is shown in Table 3 below.

Table 3 Apparatus settings for specific mean specimen temperatures

Plate	T_{MEAN} = 20 °C	T_{MEAN} = 48 °C	T_{MEAN} = 55 °C	T_{MEAN} = 72 °C
Upper	27.5 °C	55.5 °C	62.5 °C	79.5 °C
Lower	12.5 °C	40.5 °C	47.5 °C	64.5 °C

The specimen thickness was changed for certain sets of tests to obtain thermal conductivity values for estimating the single layer thickness of each protective clothing material. The Rapid-k apparatus is not capable of measuring thermal conductivity of a single layer thickness of a fabric or other protective garment material. Therefore, a test plan was developed to produce data forming a linear relationship for thermal conductivity relative to specimen thickness. This method would allow for calculating an estimate of thermal conductivity for a single thickness or layer of material. The following procedure was used to develop these estimates. This procedure was done on the material when it was first received from the manufacturing and then repeated after it had undergone the conditioning process.

> An approximately 25 mm high stack of each material was constructed by placing single layers of the same material on top of each other. Each stack of material was tested at each of the given mean test temperatures, and the thermal conductivity was recorded.
>
> For the next set of tests, 1/3 of the materials layers were removed leaving a stack consisting of 2/3 of the original number of material layers. Each stack of material was again tested at each of the mean test temperatures with the thermal conductivity being recorded.
>
> The final series of tests were conducted with the material thickness consisting of 1/3 of the original layers of material. Again each stack of material was tested at each of the mean temperatures, and the thermal conductivity was measured.

Table 4 below provides information on the number of layers used to obtain the test thickness for each stack of materials.

Table 4 Number of single layers to form stacks of material for testing

	Thickness		
Material	Full Thickness	2/3	1/3
Three Layer AraFlo® with Chambry Face Cloth	11	8	4
Two Layer AraFlo® with Glide™ Face Cloth	16	10	5
Aralite®	9	6	3
Black Fusion™	55	36	18
Black Basofil® Kevlar®	37	24	12
PBI® Kevlar® Kombat™	34	23	11
Nomex® III Defender™	35	23	12
Crosstech® on Nomex®	64	42	21
PTFE on non woven Nomex®	28	18	9
Nomex® IIIA Pajama Check	61	39	19

Three replicate tests were conducted on each of the materials, at each mean temperature setting, and each specimen stack thickness. Before material specimens can be tested, SRM 1450c is used to calibrate the test apparatus at the four selected mean test temperatures. Calibration values for SRM 1450c are shown in Figure 2. Calibration using the SRM provides the apparatus computer program with a reference thermal conductivity for the mean temperature setting. This reference value is calculated from the response of the apparatus heat flow meter. After the calibration is completed and verified, testing is begun. The mass of each test specimen stack is measured and recorded. The specimen stack is placed into the test apparatus and positioned on the lower plate. The test apparatus is closed by raising the lower plate and specimen until the specimen's top surface is in direct contact with the upper plate. The specimen and lower plate are locked into place. A transducer attached to the lower plate of the apparatus provides a measurement of specimen thickness, and specimen density is calculated using the mass data developed earlier. The test apparatus remains in an automatic mode throughout the test period when the specimen reaches a steady-state temperature condition. At this point, the computer program calculates and records the specimen's thermal conductivity.

5 Uncertainty

Measurement uncertainty for thermal conductivity with the ASTM C 518 test apparatus and procedure is significantly affected by the calibrations with SRM 1450c. Uncertainty values for SRM 1450c were reported to be less than ±2 % of the mean certified value across the temperature range used for certification [7]. A series of replicate comparative calibration tests was carried out during this study to better characterize test variability using the Rapid-k and SRM 1450c. These calibration tests were conducted at each of the four test temperature settings, 20 °C (68 °F), 48 °C (118 °F), 55 °C (131 °F), and 72 °C (162 °F). Results from these tests showed the following maximum deviations from the certified SRM values: 1 % at 20 °C (68 °F), 1 % at 48 °C (118 °F), 2 % at 55 °C (131 °F), and 5 % at 72 °C (162 °F). These calibration data indicate that measurement uncertainty is increasing as test temperatures are increased. This uncertainty becomes a component of uncertainty for thermal conductivity measurements reported in this document. The Rapid-k test apparatus precision reported by the manufacturer indicates that apparatus reproducibility is on the order of ±1 % [10]. Additionally, inter-laboratory imprecision reported in the ASTM C 518 standard, for thermal conductivity measurements using various types of insulating materials, ranged from 1.9 % to 10.5 % at a two standard deviation level.

There are different components of uncertainty in the thickness and mass of the materials data reported here. Uncertainties are grouped into two categories according to the method used to estimate them. Type A uncertainties are those which are evaluated by statistical methods, and Type B are those which are evaluated by other means [11]. Type B analysis of systematic uncertainties involves estimating the upper (+ a) and lower (- a) limits for the quantity in question such that the probability that the value would be in the interval (± a) is essentially 100 percent. After estimating uncertainties by either Type A or B analysis, the uncertainties are combined in quadrature to yield the combined standard uncertainty. Multiplying the combined standard uncertainty by a coverage factor of two results in the expanded uncertainty which corresponds to a 95 percent confidence interval.

Components of uncertainty are tabulated in Table 5 below. Some of these components, such as temperature elements, are derived from instrument specifications, while other components, such as mass and dimensional measurements include past experience.

Table 5 Uncertainty in Experimental Data

	Component Standard Uncertainty	Combined Standard Uncertainty	Total Expanded Uncertainty
Temperature		± 3 %	± 6 %
Repeatability	± 2 %		
Random	± 2 %		
Volume		± 2 %	± 4 %
Thickness	± 1 %		
Length	± 1 %		
Width	± 1 %		
Mass		± 1 %	± 3 %
Repeatability	± 1 %		
Random	± 1 %		
Density		± 5 %	± 10 %
Volume	± 4 %		
Mass	± 3 %		
Thermal Conductivity		± 7 %	± 13 %
Calibration	± 5 %		
Repeatability	± 2 %		
Random	± 4 %		

6 Results

Data from each of the test conditions, temperature and number of material layers, were reduced by linear regression, and the single layer thermal conductivity was estimated using the generated linear equation for each material and condition combination. Test results for both unconditioned and conditioned materials are shown in Table 6 through Table 25. These data show that the average thermal conductivity values generally increased as exposure temperature increases for both unconditioned and conditioned materials. The uncertainty associated with each of the single layer thermal conductivity values was determined by a method described by Natrella [12].

The effect of the conditioning process caused an increase in material thickness in seven out of the 10 materials. One moisture barrier, Nomex® IIA Pajama Check, and two of the outer shell materials, Nomex® III Defender and PBI® Kevlar® Kombat®, did not show an increase in thickness. All materials showed a decrease in density. This decrease in density was caused by a combination of increase in the material thickness along with some loss of actual material in the conditioning process.

Except for the Black Fusion™ outer shell material, there did not appear to be any significant difference between unconditioned and conditioned materials. This would indicate that the insulative properties of the materials are essentially the same before and after this conditioning process. Figure 3 through Figure 12 compare unconditioned versus conditioned thermal conductivities for each material at the four temperatures for which thermal conductivity was of interest. A possible reason for the difference in the Black Fusion™ results may be the increase in material thickness after under going the conditioning process. Black Fusion™ thickness increased approximately 17%, the greatest increase of any material.

As a comparison, the following are thermal conductivity values reported for some other similar materials. Cotton, 0.071 W/m K [13] and 0.0716 W/m K [14]; wool felt, 0.0519 W/m K [15]; wool 0.0540 W/m K [13] and 0.0528 W/m K [14]; protective clothing shell fabric, 0.0470 W/m K [16]; mineral fiber blanket 0.038 W/m K [17]. Thermal conductivity values for these materials generally fall within the range measured for materials studied in this project.

7 Conclusions

Ten materials typically used in the fabrication of fire fighters' protective clothing were tested to develop thermal conductivity estimates. Thermal conductivity was measured twice for all materials. Once when the material was new and once after the material had undergone a conditioning process of five washings and dryings by a contract cleaner that specializes in cleaning, decontaminating and repair of fire fighters' protective clothing. These fire fighters' protective clothing materials included outer shell fabrics, moisture barriers, and thermal liner batting. Thermal conductivity was measured using a commercially manufactured test apparatus. Testing followed procedures presented in ASTM C 518. The materials were tested at a mean room temperature of 20 °C (68 °F) and across a range of temperatures, 48 °C (118 °F), 55 °C (131 °F), and 72 °C (162 °F), known to produce burn injuries in humans.

Thermal conductivity values generated in this study along with the work of Lawson and Pinder will provide an initial set of data of actual protective clothing materials that may be used by computer models for predicting the thermal performance of fire fighters' protective clothing. Although this data is over a limited temperature range, some differences were measured. In general, little difference was measured between conditioned and unconditioned materials over this temperature range. It would be of interest to determine the thermal conductivity at greater temperatures, but below the temperature where material degradation begins. Current computer based heat transfer models also require input data for specific heat, emissivity, transmissivity, and reflectivity. Additional work is being conducted to develop these thermal properties for fire fighters' protective clothing.

8 Acknowledgements

Appreciation is extended to Mr. Robert T. McCarthy of the United States Fire Administration for assistance provided during this project. The United States Fire Administration provided funding for the National Institute of Standards and Technology, Building and Fire Research Laboratory to study the thermal properties of fire fighters' protective clothing. Appreciation is extended to Mr. Donald Aldridge of Lion Apparel for supplying the six additional materials.

Table 6 Thermal conductivity data of unconditioned three layer AraFlo® with Chambry face cloth thermal liner.

Experiment Temperature (°C)	Number of Layers	Measurement #1 (W/m K)	Measurement #2 (W/m K)	Measurement #3 (W/m K)	Average (W/m K)	Estimate for one layer (W/m K)
20	11	0.0331	0.0333	0.0339	0.0334	
	8	0.0335	0.0339	0.0339	0.0338	
	4	0.0335	0.0335	0.0337	0.0335	
	1					0.034±0.001
48	11	0.0361	0.0351	0.0376	0.0363	
	8	0.0393	0.0380	0.0379	0.0384	
	4	0.0402	0.0393	0.0398	0.0397	
	1					0.041±0.002
55	11	0.0370	0.0346	0.0381	0.0366	
	8	0.0408	0.0395	0.0390	0.0398	
	4	0.0447	0.0413	0.0420	0.0427	
	1					0.045±0.003
72	11	0.0426	0.0426	0.0404	0.0419	
	8	0.0431	0.0425	0.0421	0.0426	
	4	0.0495	0.0449	0.0459	0.0468	
	1					0.049±0.003

Table 7 Thermal conductivity data of conditioned three layer AraFlo® with Chambry face cloth thermal liner.

Experiment Temperature (°C)	Number of Layers	Measurement #1 (W/m K)	Measurement #2 (W/m K)	Measurement #3 (W/m K)	Average (W/m K)	Estimate for one layer (W/m K)
20	11	0.0344	0.0350	0.0339	0.0344	
	8	0.0340	0.0337	0.0334	0.0337	
	4	0.0343	0.0340	0.0341	0.0341	
	1					0.034±0.001
48	11	0.0385	0.0393	0.0371	0.0383	
	8	0.0381	0.0371	0.0379	0.0377	
	4	0.0404	0.0403	0.0401	0.0403	
	1					0.041±0.002
55	11	0.0379	0.0370	0.0365	0.0372	
	8	0.0384	0.0373	0.0385	0.0381	
	4	0.0430	0.0424	0.0425	0.0426	
	1					0.045±0.002
72	11	0.0380	0.0368	0.0418	0.0389	
	8	0.0431	0.0360	0.0427	0.0406	
	4	0.0466	0.0467	0.0456	0.0463	
	1					0.049±0.005

Table 8 Thermal conductivity data of unconditioned two layer AraFlo® with Glide™ face cloth thermal liner.

Experiment Temperature (°C)	Number of Layers	Measurement #1 (W/m K)	Measurement #2 (W/m K)	Measurement #3 (W/m K)	Average (W/m K)	Estimate for one layer (W/m K)
20	16	0.0355	0.0351	0.0356	0.0354	
	10	0.0352	0.0353	0.0354	0.0353	
	5	0.0353	0.0349	0.0361	0.0354	
	1					0.035±0.001
48	16	0.0389	0.0389	0.0384	0.0387	
	10	0.0401	0.0404	0.0406	0.0404	
	5	0.0415	0.0405	0.0422	0.0414	
	1					0.043±0.001
55	16	0.0388	0.0395	0.0383	0.0388	
	10	0.0416	0.0418	0.0423	0.0419	
	5	0.0443	0.0423	0.0445	0.0437	
	1					0.046±0.001
72	16	0.0402	0.0405	0.0407	0.0405	
	10	0.0439	0.0437	0.0447	0.0441	
	5	0.0494	0.0458	0.0491	0.0481	
	1					0.051±0.002

Table 9 Thermal conductivity data of conditioned two layer AraFlo® with Glide™ face cloth thermal liner.

Experiment Temperature (°C)	Number of Layers	Measurement #1 (W/m K)	Measurement #2 (W/m K)	Measurement #3 (W/m K)	Average (W/m K)	Estimate for one layer (W/m K)
20	16	0.0355	0.0358	0.0345	0.0353	
	10	0.0356	0.0352	0.0351	0.0353	
	5	0.0353	0.0362	0.0347	0.0354	
	1					0.036±0.001
48	16	0.0381	0.0385	0.0389	0.0385	
	10	0.0406	0.0408	0.0409	0.0408	
	5	0.0418	0.0424	0.0420	0.0420	
	1					0.044±0.001
55	16	0.0374	0.0390	0.0392	0.0386	
	10	0.0416	0.0420	0.0422	0.0419	
	5	0.0440	0.0445	0.0451	0.0445	
	1					0.047±0.001
72	16	0.0387	0.0412	0.0385	0.0395	
	10	0.0413	0.0449	0.0441	0.0434	
	5	0.0482	0.0485	0.0501	0.0490	
	1					0.053±0.003

Table 10 Thermal conductivity data of unconditioned Black Fusion™ outer shell.

Experiment Temperature (°C)	Number of Layers	Measurement #1 (W/m K)	Measurement #2 (W/m K)	Measurement #3 (W/m K)	Average (W/m K)	Estimate for one layer (W/m K)
20	55	0.0587	0.0604	0.0597	0.0596	
	36	0.0592	0.0606	0.0619	0.0606	
	18	0.0588	0.0586	0.0655	0.0610	
	1					0.062±0.005
48	55	0.0662	0.0637	0.0677	0.0659	
	36	0.0678	0.0695	0.0695	0.0689	
	18	0.0702	0.0691	0.0768	0.0720	
	1					0.075±0.005
55	55	0.0682	0.0665	0.0698	0.0682	
	36	0.0750	0.0724	0.0722	0.0732	
	18	0.0755	0.0737	0.0831	0.0774	
	1					0.082±0.006
72	55	0.0729	0.0660	0.0724	0.0704	
	36	0.0803	0.0769	0.0777	0.0783	
	18	0.0835	0.0819	0.0921	0.0858	
	1					0.093±0.007

Table 11 Thermal conductivity data of conditioned Black Fusion™ outer shell.

Experiment Temperature (°C)	Number of Layers	Measurement #1 (W/m K)	Measurement #2 (W/m K)	Measurement #3 (W/m K)	Average (W/m K)	Estimate for one layer (W/m K)
20	55	0.0579	0.0555	0.0562	0.0565	
	36	0.0585	0.0559	0.0564	0.0569	
	18	0.0567	0.0552	0.0552	0.0557	
	1					0.056±0.002
48	55	0.0602	0.0602	0.0607	0.0604	
	36	0.0655	0.0650	0.0636	0.0647	
	18	0.0663	0.0649	0.0654	0.0656	
	1					0.069±.0.002
55	55	0.0599	0.0610	0.0632	0.0613	
	36	0.0686	0.0673	0.0654	0.0671	
	18	0.0701	0.0686	0.0692	0.0693	
	1					0.074±0.003
72	55	0.0559	0.0586	0.0622	0.0589	
	36	0.0717	0.0677	0.0653	0.0682	
	18	0.0761	0.0751	0.0752	0.0754	
	1					0.083±0.005

Table 12 Thermal conductivity data of unconditioned Black Basofil® Kevlar® outer shell.

Experiment Temperature (°C)	Number of Layers	Measurement #1 (W/m K)	Measurement #2 (W/m K)	Measurement #3 (W/m K)	Average (W/m K)	Estimate for one layer (W/m K)
20	37	0.0594	0.0613	0.0614	0.0607	
	24	0.0594	0.0589	0.0603	0.0596	
	12	0.0611	0.0599	0.0594	0.0601	
	1					0.060±0.002
48	37	0.0675	0.0670	0.0676	0.0674	
	24	0.0671	0.0673	0.0689	0.0680	
	12	0.0721	0.0708	0.0704	0.0711	
	1					0.072±0.002
55	37	0.0702	0.0695	0.0698	0.0698	
	24	0.0725	0.0702	0.0721	0.0718	
	12	0.0769	0.0758	0.0755	0.0761	
	1					0.078±0.002
72	37	0.0689	0.0687	0.0685	0.0687	
	24	0.0761	0.0752	0.0763	0.0762	
	12	0.0838	0.0838	0.0825	0.0834	
	1					0.090±0.001

Table 13 Thermal conductivity data of conditioned Black Basofil® Kevlar® outer shell.

Experiment Temperature (°C)	Number of Layers	Measurement #1 (W/m K)	Measurement #2 (W/m K)	Measurement #3 (W/m K)	Average (W/m K)	Estimate for one layer (W/m K)
20	37	0.0583	0.0604	0.0604	0.0597	
	24	0.0590	0.0593	0.0604	0.0596	
	12	0.0599	0.0563	0.0570	0.0578	
	1					0.057±0.003
48	37	0.0637	0.0658	0.0660	0.0652	
	24	0.0676	0.0676	0.0688	0.0680	
	12	0.0709	0.0671	0.0682	0.0687	
	1					0.071±0.004
55	37	0.0666	0.0678	0.0689	0.0678	
	24	0.0703	0.0701	0.0730	0.0711	
	12	0.0749	0.0711	0.0720	0.0727	
	1					0.076±0.005
72	37	0.0656	0.0656	0.0690	0.0667	
	24	0.0747	0.0768	0.0787	0.0767	
	12	0.0823	0.0809	0.0792	0.0808	
	1					0.089±0.009

Table 14 Thermal conductivity data of unconditioned Crosstech® on Nomex® moisture barrier.

Experiment Temperature (°C)	Number of Layers	Measurement #1 (W/m K)	Measurement #2 (W/m K)	Measurement #3 (W/m K)	Average (W/m K)	Estimate for one layer (W/m K)
20	64	0.0490	0.0492	0.0501	0.0493	
	42	0.0488	0.0491	0.0488	0.0489	
	21	0.0492	0.0496	0.0491	0.0493	
	1					0.049±.0.001
48	64	0.0564	0.0548	0.0575	0.0561	
	42	0.0555	0.0552	0.0561	0.0556	
	21	0.0575	0.0570	0.0570	0.0572	
	1					0.057±0.002
55	64	0.0588	0.0569	0.0578	0.0576	
	42	0.0581	0.0577	0.0582	0.0580	
	21	0.0612	0.0600	0.0599	0.0604	
	1					0.061±0.002
72	64	0.0591	0.0557	0.0572	0.0573	
	42	0.0617	0.0615	0.0614	0.0615	
	21	0.0658	0.0652	0.0651	0.0654	
	1					0.069±0.002

Table 15 Thermal conductivity data of conditioned Crosstech® on Nomex® moisture barrier.

Experiment Temperature (°C)	Number of Layers	Measurement #1 (W/m K)	Measurement #2 (W/m K)	Measurement #3 (W/m K)	Average (W/m K)	Estimate for one layer (W/m K)
20	64	0.0475	0.0467	0.0479	0.0473	
	42	0.0481	0.0489	0.0490	0.0487	
	21	0.0480	0.0482	0.0478	0.0480	
	1					0.049±0.001
48	64	0.0553	0.0529	0.0542	0.0541	
	42	0.0561	0.0558	0.0565	0.0561	
	21	0.0561	0.0565	0.0557	0.0561	
	1					0.057±0.002
55	64	0.0558	0.0533	0.0567	0.0553	
	42	0.0582	0.0575	0.0577	0.0578	
	21	0.0604	0.0589	0.0592	0.0595	
	1					0.062±0.002
72	64	0.0492	0.0507	0.0546	0.0515	
	42	0.0599	0.0590	0.0578	0.0589	
	21	0.0648	0.0648	0.0630	0.0642	
	1					0.070±0.004

Table 16 Thermal conductivity data of unconditioned PTFE on non woven Nomex® moisture barrier.

Experiment Temperature (°C)	Number of Layers	Measurement #1 (W/m K)	Measurement #2 (W/m K)	Measurement #3 (W/m K)	Average (W/m K)	Estimate for one layer (W/m K)
20	28	0.0336	0.0334	0.0332	0.0334	
	18	0.0334	0.0335	0.0335	0.0335	
	9	0.0340	0.0338	0.0344	0.0341	
	1					0.034±0.001
48	28	0.0372	0.0372	0.0361	0.0368	
	18	0.0384	0.0387	0.0389	0.0386	
	9	0.0397	0.0392	0.0400	0.0396	
	1					0.041±0.001
55	28	0.0373	0.0383	0.0369	0.0375	
	18	0.0400	0.0400	0.0402	0.0399	
	9	0.0420	0.0412	0.0417	0.0416	
	1					0.044±0.001
72	28	0.0409	0.0392	0.0388	0.0396	
	18	0.0428	0.0428	0.0435	0.0429	
	9	0.0457	0.0444	0.0450	0.0450	
	1					0.048±0.002

Table 17 Thermal conductivity data of conditioned PTFE on non woven Nomex® moisture barrier.

Experiment Temperature (°C)	Number of Layers	Measurement #1 (W/m K)	Measurement #2 (W/m K)	Measurement #3 (W/m K)	Average (W/m K)	Estimate for one layer (W/m K)
20	28	0.0336	0.0333	0.0334	0.0334	
	18	0.0334	0.0327	0.0338	0.0333	
	9	0.0332	0.0334	0.0337	0.0334	
	1					0.033±0.001
48	28	0.0398	0.0377	0.0380	0.0385	
	18	0.0388	0.0375	0.0397	0.0387	
	9	0.0393	0.0392	0.0390	0.0392	
	1					0.039±0.002
55	28	0.0386	0.0365	0.0387	0.0380	
	18	0.0398	0.0397	0.0398	0.0398	
	9	0.0409	0.0414	0.0410	0.0411	
	1					0.043±0.001
72	28	0.0409	0.0370	0.0385	0.0388	
	18	0.0413	0.0421	0.0417	0.0417	
	9	0.0444	0.0453	0.0451	0.0449	
	1					0.047±0.002

Table 18 Thermal conductivity data of unconditioned PBI® Kevlar® Kombat® outer shell*.

Experiment Temperature (°C)	Number of Layers	Measurement #1 (W/m K)	Measurement #2 (W/m K)	Average (W/m K)	Estimate for one layer (W/m K)
20	34	0.0575	0.0583	0.0579	
	23	0.0564	0.0564	0.0564	
	11	0.0509	0.0508	0.0509	
	1				0.048±0.003
48	34	0.0668	0.0655	0.0622	
	23	0.0671	0.0672	0.0671	
	11	0.0686	0.0686	0.0686	
	1				0.070±0.001
55	34	0.0644	0.0645	0.0645	
	23	0.0669	0.0670	0.0669	
	11	0.0705	0.0706	0.0706	
	1				0.073±0.001
72	34	0.0675	0.0676	0.0676	
	23	0.0755	0.0755	0.0755	
	11	0.0786	0.0780	0.0783	
	1				0.084±0.005

* Data from Lawson and Pinder [3]

Table 19 Thermal conductivity data of conditioned PBI® Kevlar® Kombat® outer shell.

Experiment Temperature (°C)	Number of Layers	Measurement #1 (W/m K)	Measurement #2 (W/m K)	Measurement #3 (W/m K)	Average (W/m K)	Estimate for one layer (W/m K)
20	34	0.0552	0.0586	0.0572	0.0568	
	23	0.0474	0.0553	0.0548	0.0525	
	11	0.0496	0.0528	0.0571	0.0532	
	1					0.051±0.007
48	34	0.0606	0.0637	0.0628	0.0624	
	23	0.0539	0.0623	0.0628	0.0597	
	11	0.0594	0.0630	0.0689	0.0637	
	1					0.063±0.008
55	34	0.0604	0.0660	0.0644	0.0639	
	23	0.0567	0.0662	0.0659	0.0630	
	11	0.0631	0.0666	0.0737	0.0678	
	1					0.069±0.009
72	34	0.0552	0.0647	0.0662	0.0637	
	23	0.0849	0.0730	0.0714	0.0764	
	11	0.0702	0.0782	0.0798	0.0761	
	1					0.084±0.014

Table 20 Thermal conductivity data of unconditioned Nomex® III Defender™ outer shell*.

Experiment Temperature (°C)	Number of Layers	Measurement #1 (W/m K)	Measurement #2 (W/m K)	Average (W/m K)	Estimate for one layer (W/m K)
20	35	0.0519	0.0512	0.0516	
	23	0.0495	0.0494	0.0495	
	12	0.0497	0.0498	0.0498	
	1				0.049±0.002
48	35	0.0604	0.0593	0.0599	
	23	0.0599	0.0599	0.0599	
	12	0.0622	0.0620	0.0621	
	1				0.063±0.002
55	35	0.0611	0.0584	0.0598	
	23	0.0627	0.0618	0.0623	
	12	0.0653	0.0655	0.0654	
	1				0.068±0.003
72	35	0.0617	0.0613	0.0615	
	23	0.0655	0.0650	0.0653	
	12	0.0683	0.0682	0.0683	
	1				0.072±0.001

* Data from Lawson and Pinder [3]

Table 21 Thermal conductivity data of conditioned Nomex® III Defender™ outer shell.

Experiment Temperature (°C)	Number of Layers	Measurement #1 (W/m K)	Measurement #2 (W/m K)	Measurement #3 (W/m K)	Average (W/m K)	Estimate for one layer (W/m K)
20	35	0.0508	0.0516	0.0518	0.0514	
	23	0.0507	0.0491	0.0502	0.0500	
	12	0.0498	0.0466	0.0499	0.0488	
	1					0.048±0.002
48	35	0.0579	0.0557	0.0561	0.0565	
	23	0.0587	0.0558	0.0581	0.0575	
	12	0.0592	0.0555	0.0596	0.0581	
	1					0.059±0.003
55	35	0.0583	0.0581	0.0590	0.0585	
	23	0.0615	0.0590	0.0612	0.0606	
	12	0.0625	0.0586	0.0627	0.0613	
	1					0.063±0.003
72	35	0.0554	0.0576	0.0597	0.0575	
	23	0.0663	0.0645	0.0659	0.0655	
	12	0.0682	0.0655	0.0689	0.0676	
						0.073±0.004

Table 22 Thermal conductivity data of unconditioned Nomex® IIIA Pajama Check moisture barrier*.

Experiment Temperature (°C)	Number of Layers	Measurement #1 (W/m K)	Measurement #2 (W/m K)	Average (W/m K)	Estimate for one layer (W/m K)
20	61	0.0463	0.0466	0.0464	
	39	0.0470	0.0472	0.0471	
	19	0.0431	0.0431	0.0431	
	1				0.042±0.004
48	61	0.0535	0.0537	0.0536	
	39	0.0577	0.0575	0.0576	
	19	0.0579	0.0574	0.0577	
	1				0.060±0.004
55	61	0.0547	0.0549	0.0548	
	39	0.0574	0.0571	0.0573	
	19	0.0599	0.0597	0.0598	
	1				0.062±0.001
72	61	0.0568	0.0558	0.0563	
	39	0.0613	0.0610	0.0612	
	19	0.0643	0.0637	0.0640	
	1				0.068±0.002

* Data from Lawson and Pinder [3]

Table 23 Thermal conductivity data of conditioned Nomex® IIIA Pajama Check moisture barrier.

Experiment Temperature (°C)	Number of Layers	Measurement #1 (W/m K)	Measurement #2 (W/m K)	Measurement #3 (W/m K)	Average (W/m K)	Estimate for one layer (W/m K)
20	61	0.0457	0.0487	0.0468	0.0471	
	39	0.0465	0.0472	0.0465	0.0467	
	19	0.0465	0.0465	0.0467	0.0466	
	1					0.046±0.002
48	61	0.0522	0.0514	0.0532	0.0523	
	39	0.0542	0.0529	0.0535	0.0535	
	19	0.0549	0.0548	0.0547	0.0548	
	1					0.056±0.001
55	61	0.0535	0.0509	0.0552	0.0532	
	39	0.0555	0.0553	0.0564	0.0557	
	19	0.0581	0.0577	0.0574	0.0578	
	1					0.060±0.003
72	61	0.0499	0.0461	0.0548	0.0503	
	39	0.0589	0.0593	0.0607	0.0596	
	19	0.0635	0.0622	0.0616	0.0624	
	1					0.069±0.006

Table 24 Thermal conductivity data of unconditioned Aralite® thermal liner*.

Experiment Temperature (°C)	Number of Layers	Measurement #1 (W/m K)	Measurement #2 (W/m K)	Average (W/m K)	Estimate for one layer (W/m K)
20	9	0.0355	0.0353	0.0354	
	6	0.0352	0.0351	0.0352	
	3	0.0354	0.0354	0.0354	
	1				0.035±0.001
48	9	0.0380	0.0385	0.0383	
	6	0.0409	0.0409	0.0409	
	3	0.0427	0.0430	0.0428	
	1				0.045±0.001
55	9	0.0386	0.0385	0.0386	
	6	0.0411	0.0411	0.0411	
	3	0.0444	0.0444	0.0444	
	1				0.046±0.001
72	9	0.0420	0.0420	0.0420	
	6	0.0447	0.0446	0.0447	
	3	0.0475	0.0476	0.0476	
	1				0.049±0.001

* Data from Lawson and Pinder [3]

Table 25 Thermal conductivity data of conditioned Aralite® thermal liner.

Experiment Temperature (°C)	Number of Layers	Measurement #1 (W/m K)	Measurement #2 (W/m K)	Measurement #3 (W/m K)	Average (W/m K)	Estimate for one layer (W/m K)
20	10	0.0344	0.0346	0.0345	0.0345	
	7	0.0342	0.0343	0.0343	0.0343	
	4	0.0344	0.0341	0.0338	0.0341	
	1					0.034±0.001
48	10	0.0357	0.0374	0.0385	0.0372	
	7	0.0395	0.0386	0.0385	0.0389	
	4	0.0399	0.0398	0.0396	0.0398	
	1					0.041±0.002
55	10	0.0356	0.0367	0.0391	0.0372	
	7	0.0411	0.0399	0.0398	0.0403	
	4	0.0418	0.0418	0.0416	0.0417	
	1					0.044±0.002
72	10	0.0364	0.0418	0.0411	0.0398	
	7	0.0438	0.0415	0.0439	0.0431	
	4	0.0453	0.0454	0.0451	0.0453	
	1					0.048±0.004

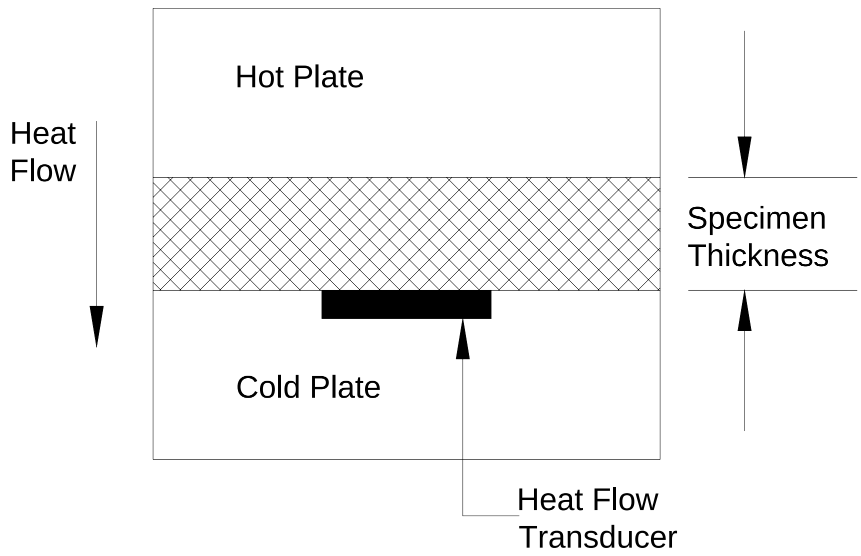

Figure 1 A schematic of the Rapid-k test section.

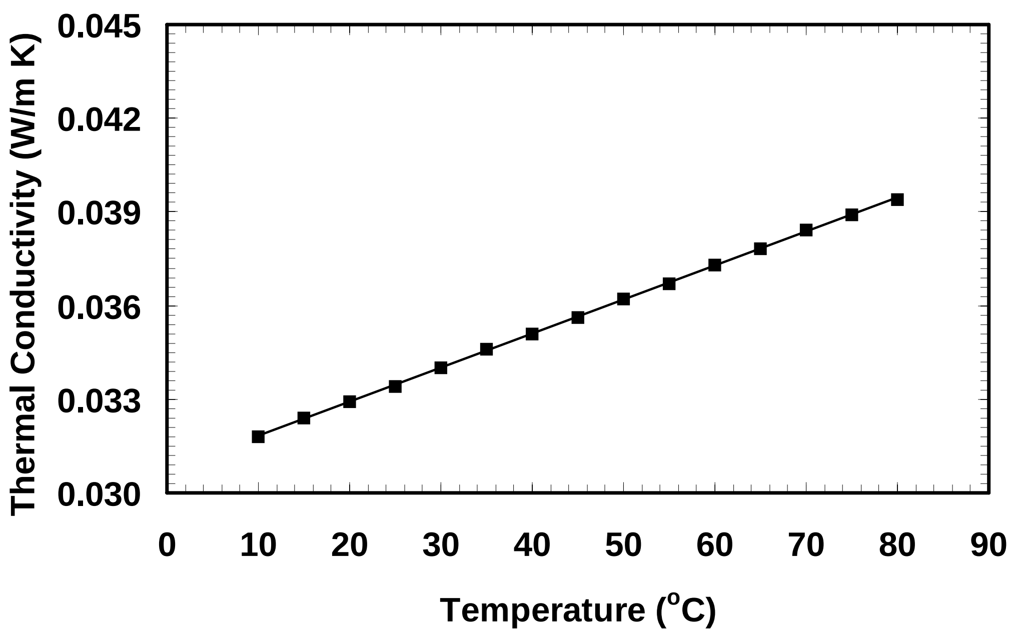

Figure 2 Calibration values for SRM 1450c as indicated by SRM certificate.

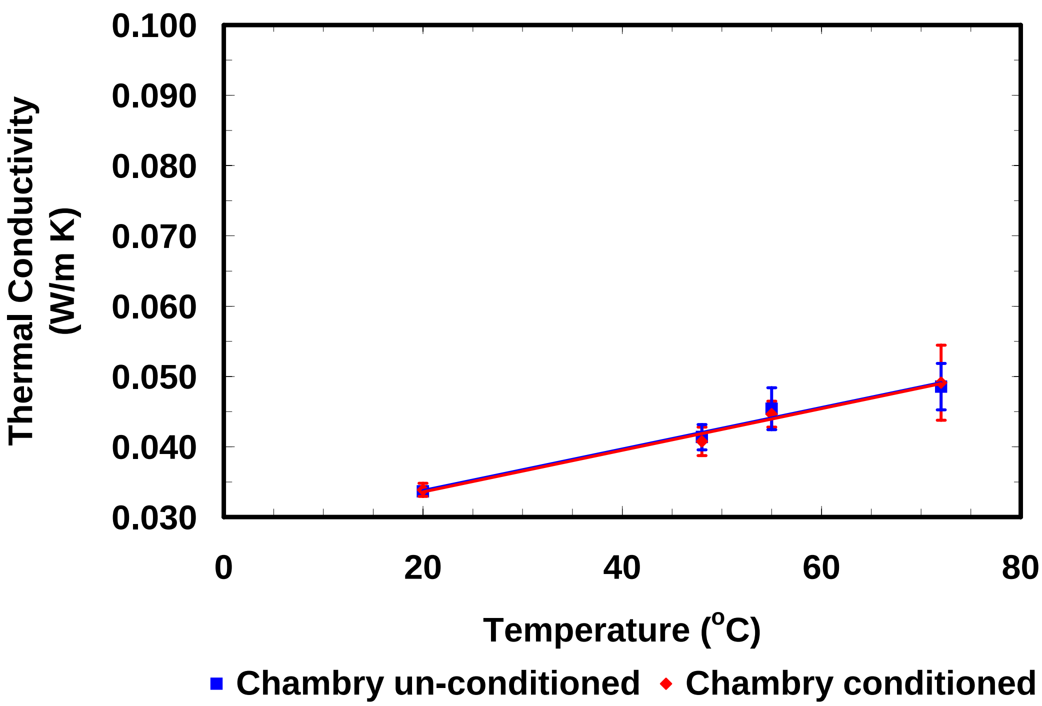

Figure 3 **Comparison of estimated thermal conductivity between unconditioned and conditioned Three Layer AraFlo® with Chambry Face Cloth thermal liner.**

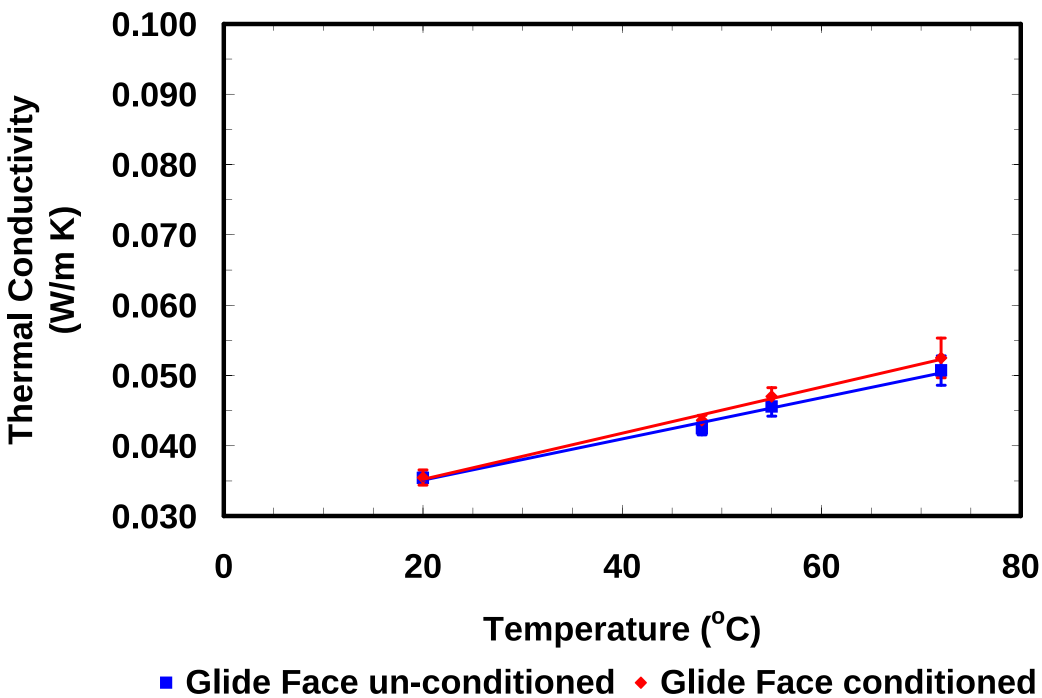

Figure 4 **Comparison of estimated thermal conductivity between unconditioned and conditioned Two Layer AraFlo® with Glide™ Face Cloth thermal liner.**

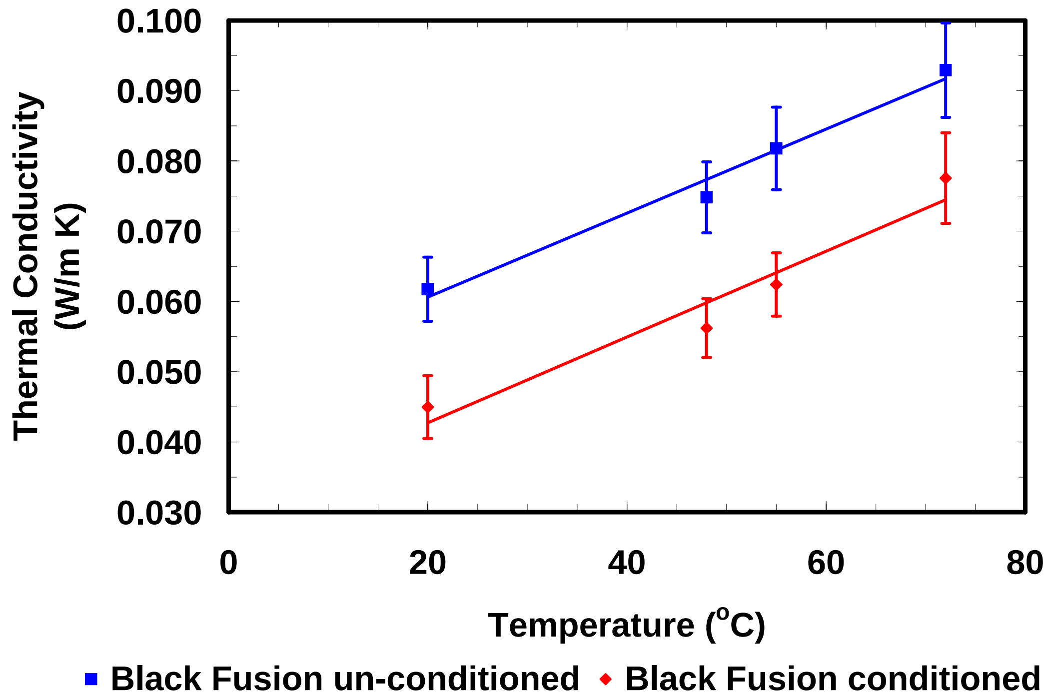

Figure 5 Comparison of estimated thermal conductivity between unconditioned and conditioned Black Fusion™ outer shell.

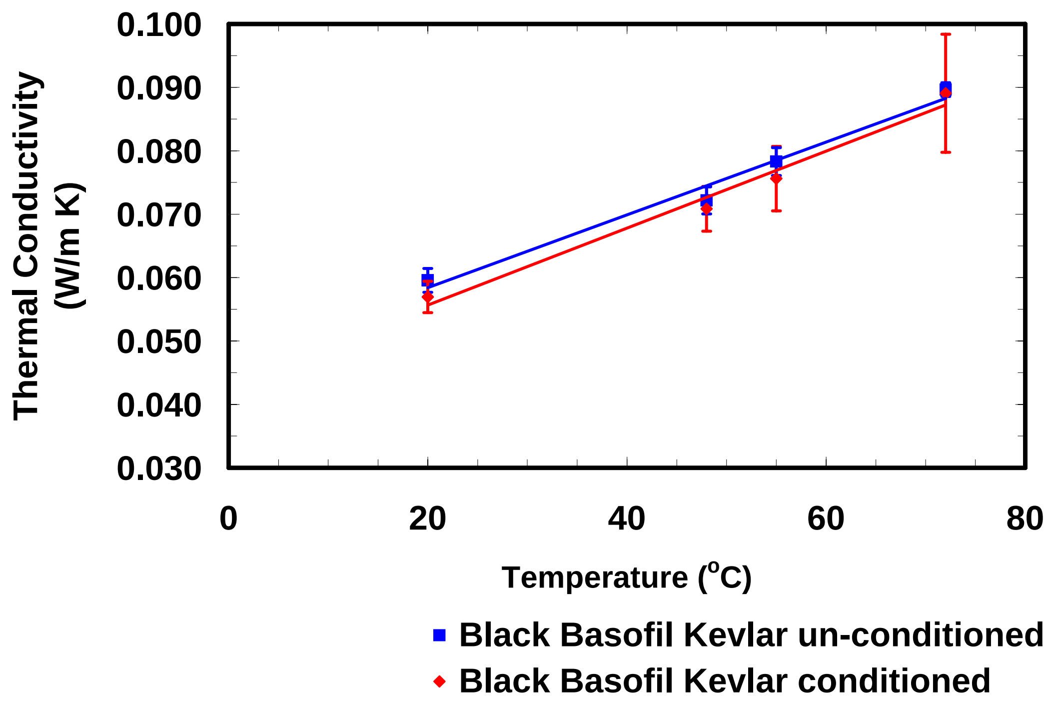

Figure 6 Comparison of estimated thermal conductivity between unconditioned and conditioned Black Basofil® Kevlar® outer shell.

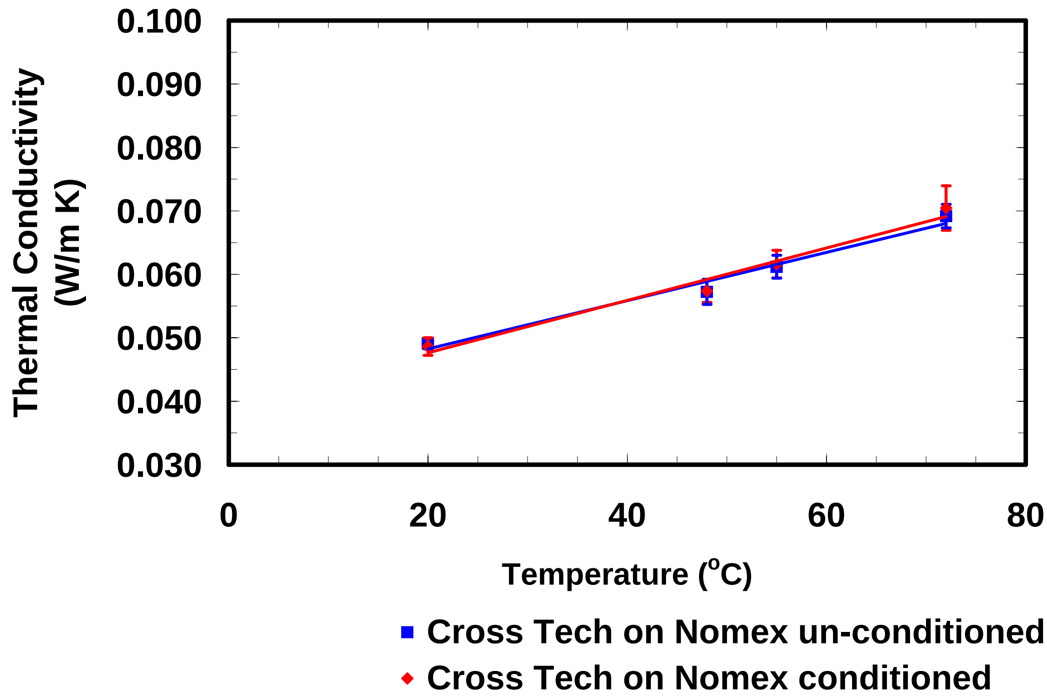

Figure 7 Comparison of estimated thermal conductivity between unconditioned and conditioned Crosstech® on Nomex® moisture barrier.

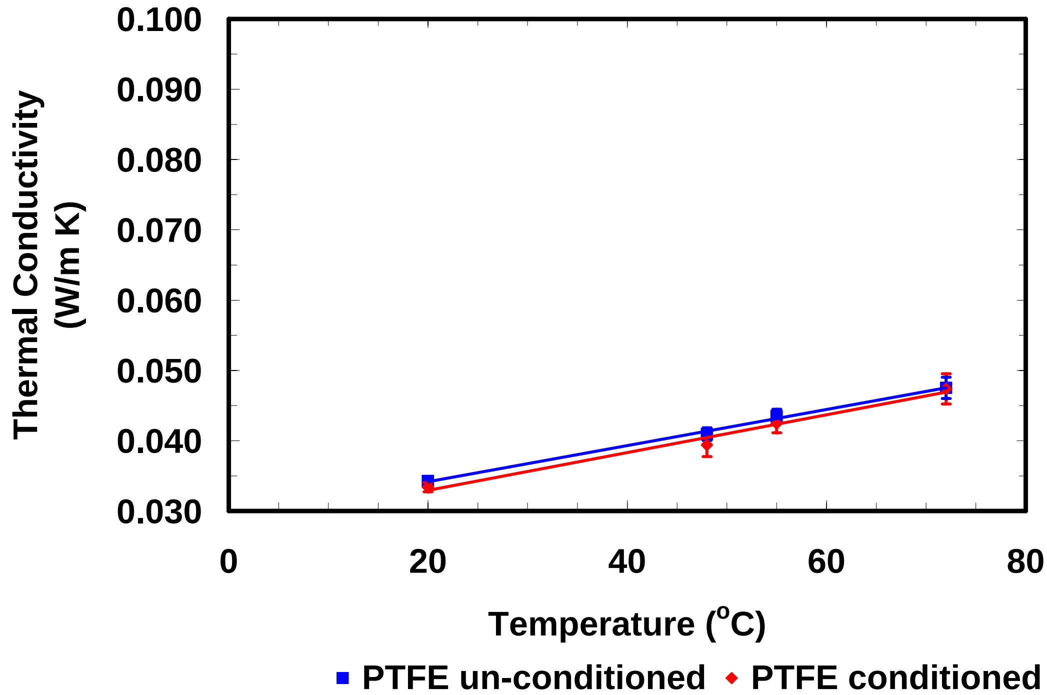

Figure 8 Comparison of estimated thermal conductivity between unconditioned and conditioned PTFE on non woven Nomex® moisture barrier.

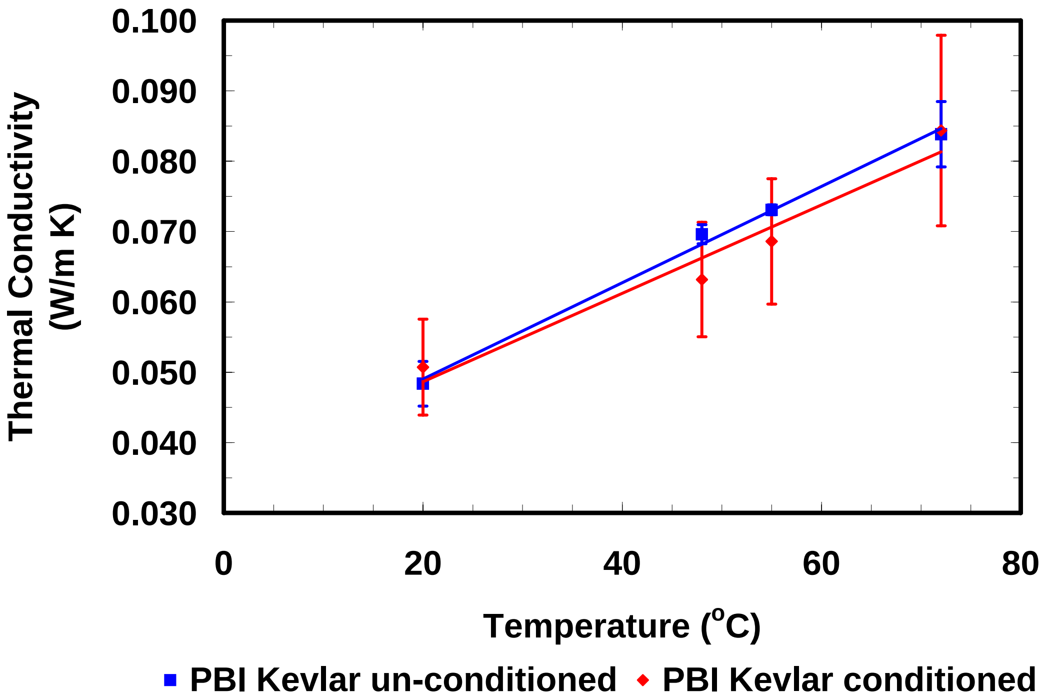

Figure 9 Comparison of estimated thermal conductivity between unconditioned and conditioned PBI® Kevlar® Kombat® outer shell.

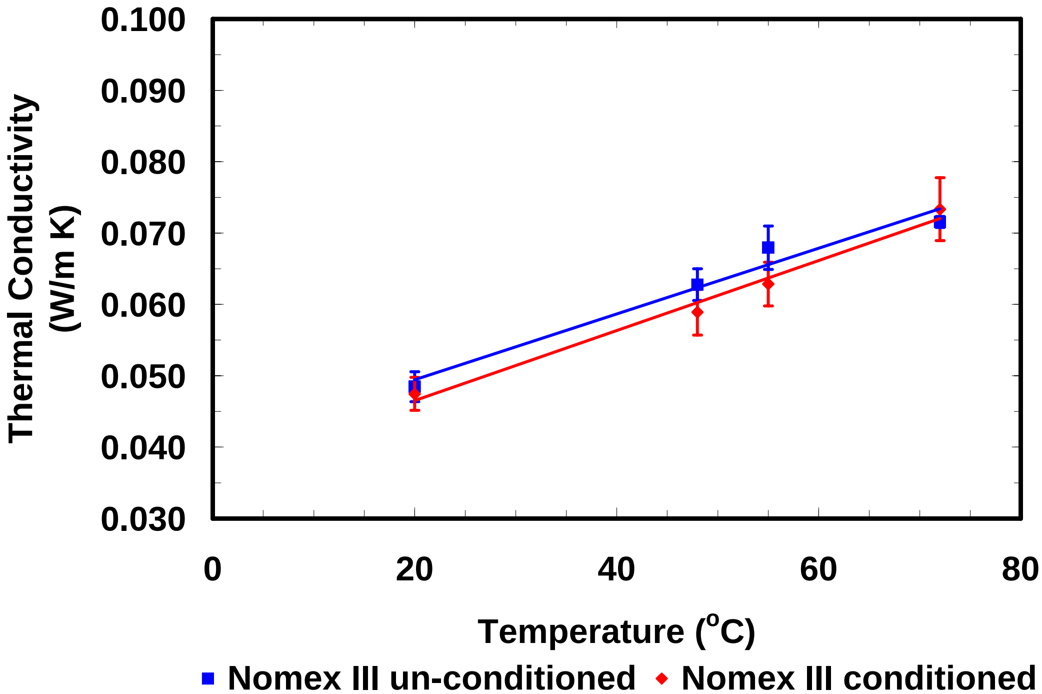

Figure 10 Comparison of estimated thermal conductivity between unconditioned and conditioned Nomex® III Defender™ outer shell.

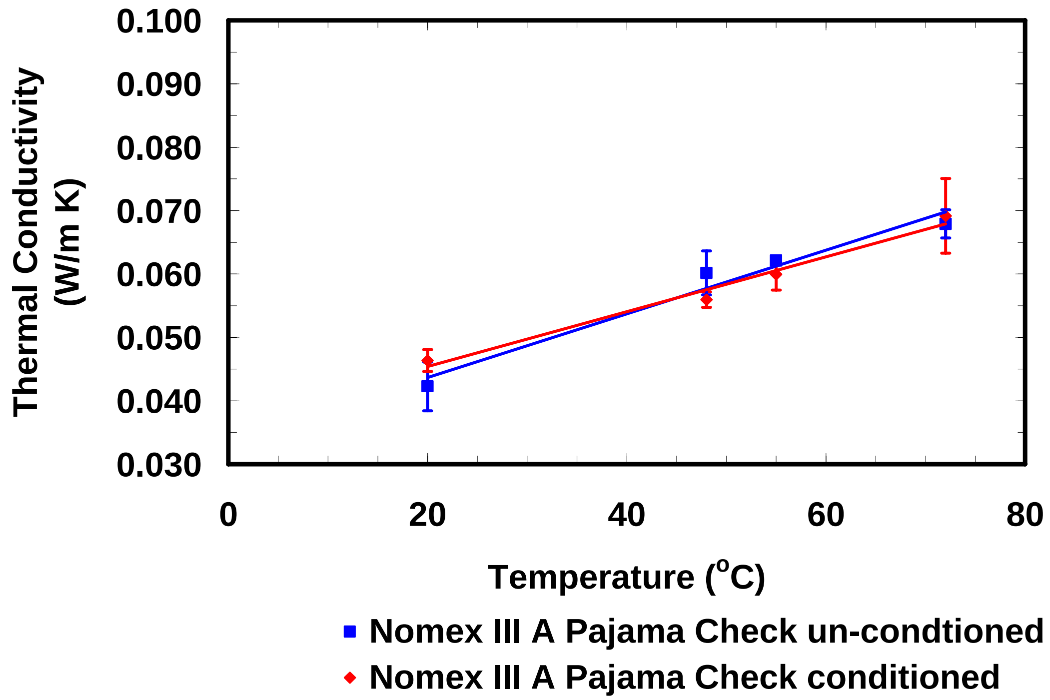

Figure 11 Comparison of estimated thermal conductivity between unconditioned and conditioned Nomex® IIIA Pajama Check moisture barrier.

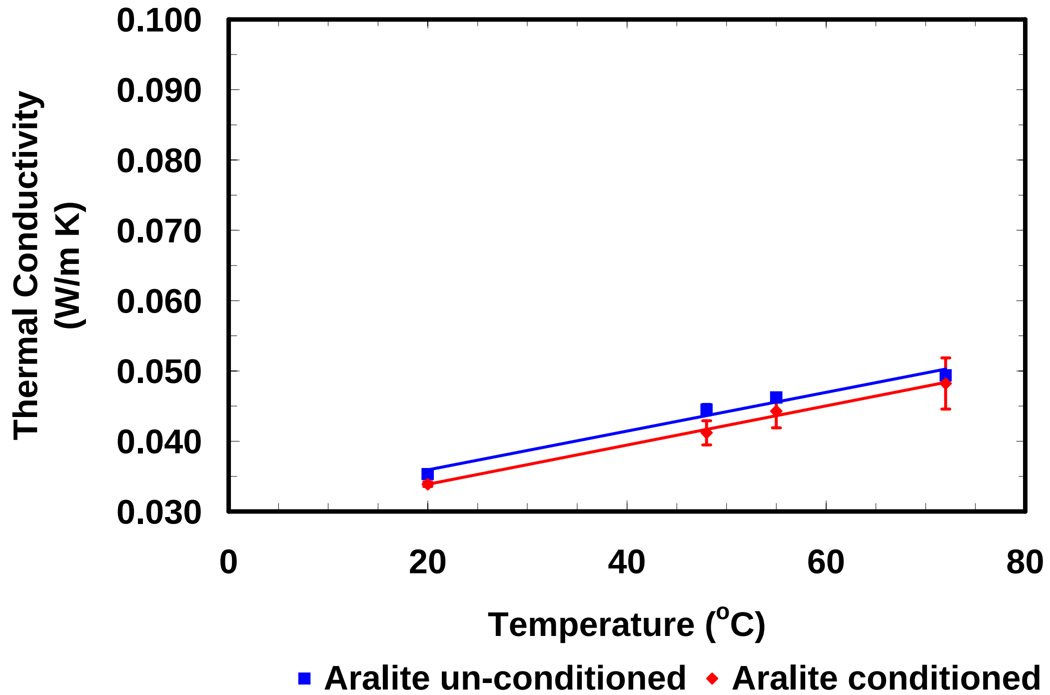

Figure 12 Comparison of estimated thermal conductivity between unconditioned and conditioned Aralite® thermal liner.

9 References

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