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

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J. Randall Lawson
Tershia A. Pinder

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J. Randall Lawson
Tershia A. Pinder

Building and Fire Research Laboratory
National Institute of Standards and Technology
Gaithersburg, MD 20899-8644

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U.S. Department of Commerce
William M. Daley, *Secretary*
Technology Administration
Dr. Cheryl L. Shavers, *Under Secretary of Commerce for Technology*
National Institute of Standards and Technology
Raymond G. Kammer, *Director*

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ESTIMATES OF THERMAL CONDUCTIVITY FOR MATERIALS USED IN FIRE FIGHTERS' PROTECTIVE CLOTHING

by

J. Randall Lawson and Tershia A. Pinder*

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 critical thermal properties of fire fighters' protective clothing materials. These thermal properties are: thermal conductivity, specific heat, and the thermal spectral properties of emissivity, transmissivity and reflectivity. This report presents thermal conductivity data for nine materials used in fabricating fire fighters' protective clothing. These materials included outer shell fabrics, moisture barrier, thermal liner batting, and reflective trim. As a comparison, measurements were also made on a cotton duck fabric. 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 [1]. Measurements producing estimates of thermal conductivity for single layers 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. Thermal conductivity estimates for materials used in the construction of fire fighters' protective clothing ranged from 0.034 W/mK to 0.136 W/mK over the range of temperatures addressed in the study. Generally, thermal conductivity values increased for all materials as mean test temperatures were increased.

KEY WORDS: Fires, fire fighters, heat transfer, protective clothing, thermal conductivity, test method

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* Ms. Pinder is currently a graduate student at the University of Michigan.

1.0 INTRODUCTION

The thermal performance of fire fighters' protective clothing is primarily based on the thermophysical properties of the materials that are used to construct the clothing. Scientific analysis and prediction of protective clothing thermal performance requires the use of numerical values of thermophysical properties for all materials used in garment construction. Currently, little information is available for making detailed studies of protective clothing thermal performance. The work discussed in this paper describes an initial attempt to develop thermophysical data on materials used in the construction of fire fighters' protective clothing. The physical properties used for thermal analysis and predictions are: thermal conductivity, specific heat, density, and the thermal spectral properties of emissivity, transmissivity and reflectivity [2]. This paper discusses measurements of thermal conductivity.

Thermal conductivity of a material relates to the rate of heat transfer through material [3]. 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 that 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 material's performance would be compromised. Testing was carried out at the following temperatures: of 20 °C (68 °F), 48 °C (118 °F), 55 °C (131 °F), and 72 °C (162 °F).

2.0 APPARATUS

The test equipment used to obtain thermal conductivity data reported in this document was constructed to operate in accordance with ASTM C 518, Standard Test Method for Steady-State Thermal Transmission Properties by Means of Heat Flow Meter Apparatus [1]. 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 control and data logging. Figure 1 shows a photograph of the test apparatus, and Fig. 2 shows the principal of the apparatus operation. The apparatus was calibrated using NIST Standard Reference Material (SRM) 1450c, a fibrous glass board insulation. This SRM measured 305 mm x 305 mm (12 in x 12 in) square 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/mK. Figure 3 shows a temperature calibration plot for SRM 1450c over the range from 10 °C (50 °F) to 90 °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.

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[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.

The ASTM C 518 standard is a comparative method for measuring thermal conductivity that is based on apparatus calibrations obtained from the SRM. 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 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 [4].

3.0 MATERIALS

Ten different materials were tested in this study. See Table 1. All of these materials except one are currently used as components of fire fighters' protective clothing. One material, the cotton duck was added to the study for comparison purposes. Some early fire fighter coats were made from cotton duck material similar to that tested; however, the cotton duck on the early coats was usually coated with rubber to repel water. That construction would be similar to the one exhibited by Neo-Guard®. Of the materials tested, five were moisture barriers, three were outer shell fabrics, one was a thermal liner, and one represented retroreflective trim used on fire fighters' protective clothing. 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*	MANUFACTURER	USE
Aralite®	Southern Mills	Thermal Liner
Breathe-Tex®	Alden Industries	Moisture Barrier
Breathe-Tex®Plus	Alden Industries	Moisture Barrier
Cotton Duck	Not Available	Outer Shell
Nomex® E-89 Crosstech®	W.L. Gore & Associates	Moisture Barrier
Neo-Guard®	Alden Industries	Moisture Barrier
Nomex® III- Defender™	Southern Mills	Outer Shell
Nomex® IIIA Pajama Check-Crosstech®	W.L. Gore & Associates	Moisture Barrier
PBI™-Kevlar®Kombat™	Southern Mills	Outer Shell
Scotchlite®	3M	Trim

* Aralite®, Defender™, and Kombat™ are registered trademarks of Southern Mills.
Breathe-Tex®, and Neo-Guard® are registered trademarks of Alden Industries.
Nomex®, and Kevlar® are registered trademarks of E.I. Du Pont.
Crosstech® is a registered trademark of W.L. Gore & Associates.
PBI™ is a registered trademark of the Celanese Corporation.
Scotchlite® is a registered trademark of 3M, Minnesota Mining and Manufacturing Company.

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) square. Specimen sizes 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 carefully 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.

Table 2 Test specimen dimensions and density.

Material	Mass (g)	Length (mm)	Width (mm)	Thickness (mm)	Density (g/cm^3)	Density (kg/m^3)
Aralite®	24.0	305	305	3.5941	0.0742	74.2
Breathe-Tex®	13.3	305	305	1.2243	0.1207	120.7
Breathe-Tex®Plus	18.0	305	305	1.1151	0.1794	179.4
Cotton Duck	61.8	305	305	1.3233	0.5189	518.9
Nomex® E-89 Crosstech®	12.4	305	305	0.9627	0.1431	143.1
Neo-Guard®	29.5	305	305	0.5486	0.5974	597.4
Nomex® III- Defender™	23.4	305	305	0.8204	0.3169	316.9
Nomex® IIIA Pajama Check® Crosstech®	14.7	305	305	0.5156	0.3168	316.8
PBI™-Kevlar® Kombat™	23.1	305	305	0.7976	0.3218	321.8
Scotchlite®	55.0	305	305	0.7493	0.0816	81.6

4.0 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 C1055, Standard Guide for Heated Systems Surface Conditions That Produce Contact Burn Injuries, and cover the range of temperatures that produce burn injuries [5]. The 20 °C (68 °F) temperature represents room temperature, 48 °C (118 °F) represents a human tissue temperature where a first degree burn occurs, 55 °C (131 °F) is the human tissue temperature that is likely to cause a second degree burn [6], and 72 °C (162 °F) is the human tissue temperature where an instantaneous burn injury is likely to occur. The following test procedures were used to measure thermal conductivity for each of the materials at each of the temperatures listed above.

4.1 CONDITIONING

Test specimens were conditioned to mass equilibrium in a controlled laboratory environment. This environment was 23 °C ±3 °C (°F 73 ±5 °F)and a 50 % ±10 % relative humidity. Test room conditions were the same as the conditioning environment.

4.2 TEST PLAN

As mentioned above, the thermal conductivity of each material was measured at four different temperatures. This 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. These apparatus temperature changes and changes in test specimen thickness represent the two parameters examined in the measurement process.

Table 3 Apparatus setting 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 development these estimates:

- A 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.

The following, Table 4, 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 materials for testing.

MATERIAL	LAYERS		
	25 mm	2/3	1/3
Aralite®	9	6	3
Breathe-Tex®	24	16	8
Breathe-Tex® Plus	26	17	9
Cotton Duck	22	15	7
Nomex® E89 Crosstech®	29	19	10
Neo-Guard®	65	43	22
Nomex® III- Defender™	35	23	12
Nomex® IIIA Pajama Check – Crosstech®	58	39	19
PBI™-Kevlar® Kombat™	34	23	11
Scotchlite® Trim	42	28	14

After all data were collected estimates of thermal conductivity were calculated for each material using linear formulas developed from the materials' thermal response.

4.3 TEST PROCEDURE

Two 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 one of the four selected mean test temperatures. Calibration values for SRM 1450c are shown in Fig. 3. 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 a 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.

5.0 PRECISION

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: ±2 % at 20 °C (68 °F), ±2 % at 48 °C (118 °F), ±3 % at 55 °C (131 °F), and ±4 % 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 % [8]. Additionally, interlaboratory 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 [1].

6.0 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 are shown in the following tables:

Table 5 Thermal conductivity data for Aralite®.

Test Temperature (°C)	Number of Layers	Measurement #1 (W/mK)	Measurement #2 (W/mK)	Average (W/mK)	Estimate for One Layer (W/mK)
20	9	0.0355	0.0353	0.0354	
	6	0.0352	0.0351	0.0352	
	3	0.0354	0.0354	0.0354	
	1				0.0353
48	9	0.0380	0.0385	0.0383	
	6	0.0409	0.0409	0.0409	
	3	0.0427	0.0430	0.0428	
	1				0.0445
55	9	0.0386	0.0385	0.0386	
	6	0.0411	0.0411	0.0411	
	3	0.0444	0.0444	0.0444	
	1				0.0462
72	9	0.0420	0.0420	0.0420	
	6	0.0447	0.0446	0.0447	
	3	0.0475	0.0476	0.0476	
	1				0.0494

Table 6 Thermal conductivity data for Breathe Tex®.

Test Temperature (°C)	Number of Layers	Measurement #1 (W/mK)	Measurement #2 (W/mK)	Average (W/mK)	Estimate for One Layer (W/mK)
20	24	0.0346	0.0345	0.0346	
	16	0.0349	0.0348	0.0349	
	8	0.0341	0.0340	0.0340	
	1				0.0340
48	24	0.0381	0.0379	0.0380	
	16	0.0401	0.0401	0.0401	
	8	0.0412	0.0411	0.0412	
	1				0.0427
55	24	0.0378	0.0372	0.0375	
	16	0.0399	0.0399	0.0399	
	8	0.0422	0.0421	0.0421	
	1				0.0441
72	24	0.0378	0.0403	0.0391	
	16	0.0426	0.0428	0.0427	
	8	0.0464	0.0463	0.0463	
	1				0.0494

Table 7 Thermal conductivity data for Breathe Tex® Plus.

Test Temperature (°C)	Number of Layers	Measurement #1 (W/mK)	Measurement #2 (W/mK)	Average (W/mK)	Estimate for One Layer (W/mK)
20	26	0.0358	0.0357	0.0358	
	17	0.0360	0.0360	0.0360	
	9	0.0366	0.0366	0.0366	
	1				0.0370
48	26	0.0399	0.0394	0.0397	
	17	0.0417	0.0415	0.0416	
	9	0.0420	0.0419	0.0420	
	1				0.0433
55	26	0.0393	0.0395	0.0394	
	17	0.0425	0.0416	0.0421	
	9	0.0439	0.0439	0.0439	
	1				0.0461
72	26	0.0424	0.0423	0.0424	
	17	0.0433	0.0438	0.0435	
	9	0.0471	0.0472	0.0472	
	1				0.0476

Table 8 Thermal conductivity data for Cotton Duck.

Test Temperature (°C)	Number of Layers	Measurement #1 (W/mK)	Measurement #2 (W/mK)	Average (W/mK)	Estimate for One Layer (W/mK)
20	22	0.0816	0.0820	0.0818	
	15	0.0864	0.0852	0.0858	
	7	0.0814	0.0813	0.0813	
	1				0.0823
48	22	0.0972	0.0956	0.0964	
	15	0.0992	0.0989	0.0990	
	7	0.1004	0.1002	0.1003	
	1				0.1020
55	22	0.1119	0.1108	0.1113	
	15	0.1037	0.1033	0.1035	
	7	0.1060	0.1051	0.1055	
	1				0.1017
72	22	0.1040	0.1025	0.1033	
	15	0.1082	0.1079	0.1081	
	7	0.1059	0.1061	0.1060	
	1				0.1081

Table 9 Thermal conductivity data for Nomex® E89 Crosstech®.

Test Temperature (°C)	Number of Layers	Measurement #1 (W/mK)	Measurement #2 (W/mK)	Average (W/mK)	Estimate for One Layer (W/mK)
20	29	0.0354	0.0354	0.0354	
	19	0.0350	0.0348	0.0349	
	10	0.0354	0.0353	0.0354	
	1				0.0352
48	29	0.0390	0.0384	0.0387	
	19	0.0410	0.0406	0.0408	
	10	0.0411	0.0410	0.0410	
	1				0.0425
55	29	0.0394	0.0388	0.0391	
	19	0.0406	0.0404	0.0405	
	10	0.0459	0.0452	0.0455	
	1				0.0479
72	29	0.0391	0.0407	0.0399	
	19	0.0436	0.0443	0.0440	
	10	0.0459	0.0459	0.0459	
	1				0.0491

Table 10 Thermal conductivity data for Neo-Guard®.

Test Temperature (°C)	Number of Layers	Measurement #1 (W/mK)	Measurement #2 (W/mK)	Average (W/mK)	Estimate for One Layer (W/mK)
20	65	0.0859	0.0857	0.0858	
	43	0.0915	0.0915	0.0915	
	22	0.06960	0.0695	0.0695	
	1				0.0664
48	65	0.0949	0.0959	0.0954	
	43	0.1061	0.1070	0.1066	
	22	0.1094	0.1088	0.1091	
	1				0.1172
55	65	0.1093	0.1084	0.1088	
	43	0.1080	0.1095	0.1086	
	22	0.0975	0.1076	0.1025	
	1				0.1005
72	65	0.1106	0.1114	0.1110	
	43	0.1193	0.1184	0.1189	
	22	0.1186	0.1203	0.1195	
	1				0.1248

Table 11 Thermal conductivity data for Nomex® III- Defender™.

Test Temperature (°C)	Number of Layers	Measurement #1 (W/mK)	Measurement #2 (W/mK)	Average (W/mK)	Estimate for One Layer (W/mK)
20	35	0.0519	0.0512	0.0515	
	23	0.0495	0.0494	0.0494	
	12	0.0497	0.0498	0.0497	
	1				0.0483
48	35	0.0604	0.0593	0.0589	
	23	0.0599	0.0599	0.0599	
	12	0.0622	0.0620	0.0621	
	1				0.0628
55	35	0.0611	0.0584	0.0598	
	23	0.0627	0.0618	0.0622	
	12	0.0653	0.0655	0.0654	
	1				0.0679
72	35	0.0617	0.0613	0.0615	
	23	0.0655	0.0650	0.0653	
	12	0.0683	0.0682	0.0682	
	1				0.0715

Table 12 Thermal conductivity data for Nomex® IIIA Pajama Check – Crosstech®.

Test Temperature (°C)	Number of Layers	Measurement #1 (W/mK)	Measurement #2 (W/mK)	Average (W/mK)	Estimate for One Layer (W/mK)
20	58	0.0463	0.0466	0.0464	
	39	0.0470	0.0472	0.0471	
	19	0.0431	0.0431	0.0431	
	1				0.0423
48	58	0.0535	0.0537	0.0536	
	39	0.0577	0.0575	0.0576	
	19	0.0579	0.0574	0.0577	
	1				0.0602
55	58	0.0547	0.0549	0.0548	
	39	0.0574	0.0571	0.0573	
	19	0.0599	0.0597	0.0598	
	1				0.0621
72	58	0.0568	0.0558	0.0563	
	39	0.0613	0.0610	0.0612	
	19	0.0643	0.0637	0.0640	
	1				0.0679

Table 13 Thermal conductivity data for PBI™-Kevlar® Kombat™.

Test Temperature (°C)	Number of Layers	Measurement #1 (W/mK)	Measurement #2 (W/mK)	Average (W/mK)	Estimate for One Layer (W/mK)
20	34	0.0575	0.0583	0.0579	
	23	0.0564	0.0564	0.0564	
	11	0.0509	0.0508	0.0509	
	1				0.0484
48	34	0.0668	0.0655	0.0662	
	23	0.0671	0.0672	0.0671	
	11	0.0686	0.0686	0.0686	
	1				0.0697
55	34	0.0644	0.0645	0.0645	
	23	0.0669	0.0670	0.0669	
	11	0.0705	0.0706	0.0706	
	1				0.0730
72	34	0.0675	0.0676	0.0676	
	23	0.0755	0.0755	0.0755	
	11	0.0786	0.0780	0.0783	
	1				0.0838

Table 14 Thermal conductivity data for Scotchlite® Trim.

Test Temperature (°C)	Number of Layers	Measurement #1 (W/mK)	Measurement #2 (W/mK)	Average (W/mK)	Estimate for One Layer (W/mK)
20	42	0.1040	0.1040	0.1040	
	28	0.1044	0.1030	0.1037	
	14	0.0832	0.0832	0.0832	
	1				0.0769
48	42	0.1207	0.1214	0.1211	
	28	0.1251	0.1254	0.1252	
	14	0.1216	0.1222	0.1219	
	1				0.1236
55	42	0.1262	0.1267	0.1264	
	28	0.1301	0.1299	0.1300	
	14	0.1261	0.1256	0.1259	
	1				0.1269
72	42	0.1297	0.1294	0.1296	
	28	0.1364	0.1369	0.1366	
	14	0.1329	0.1329	0.1329	
	1				0.1363

These data show that the average thermal conductivity values generally increased as exposure temperature increases. Only one material, Neo-Guard, showed noticeable deviation within this trend. Plots showing thermal conductivity trends are presented in Figs. 4 through Fig. 8. Note that the materials are not grouped by data plots in the same order as found in the earlier tables. Two data plots are shown on each graph. The materials selected for each graph were grouped for the purpose of producing clear data plots by minimizing cases of overlapped data.

As a comparison, the following are thermal conductivity values reported for some materials similar to those measured in this study: Cotton, 0.0589 W/mK [9]; wool felt, 0.0519 W/mK [9]; silk, 0.0364 W/mK [9]; protective clothing shell fabric, 0.0470 W/mK [10]; hard rubber, 0.1506 W/mK [9]; soft rubber, 0.012 W/mK [11]; glass wool insulation, 0.038 W/mk [11]. Thermal conductivity values for these materials generally fall within the range measured for materials studied in this project. Some variation in thermal conductivity would be expected with the comparative values shown in this paragraph since the finished form of the material and density were not generally reported by the reference documents.

7.0 SUMMARY

Nine materials typically used in the fabrication of fire fighters' protective clothing and one cotton fabric were tested to develop thermal conductivity estimates. These fire fighters' protective clothing materials included outer shell fabrics, moisture barriers, thermal liner batting, and reflective trim. Thermal conductivity was measured using a commercially manufactured test apparatus. Testing followed procedures presented in ASTM C-518 [1]. The materials were tested at a mean room temperature of 20 °C (68 °F) and across a range of skin tissue temperatures, 48 °C (118 °F), 55 °C (131 °F), and 72 °C (162 °F), known to produce burn injuries in humans. Results measured in this study compared favorably with the thermal conductivity of several other common materials. Thermal conductivity values generated in this study will provide an initial set of data for actual protective clothing materials that may be used by computer models for predicting the thermal performance of fire fighters' protective clothing. Current computer based heat transfer models also require input data for specific heat, emissivity, transmissivity, and reflectivity. Additional work is required to develop these thermal properties for fire fighters' protective clothing.

8.0 ACKNOWLEDGEMENTS

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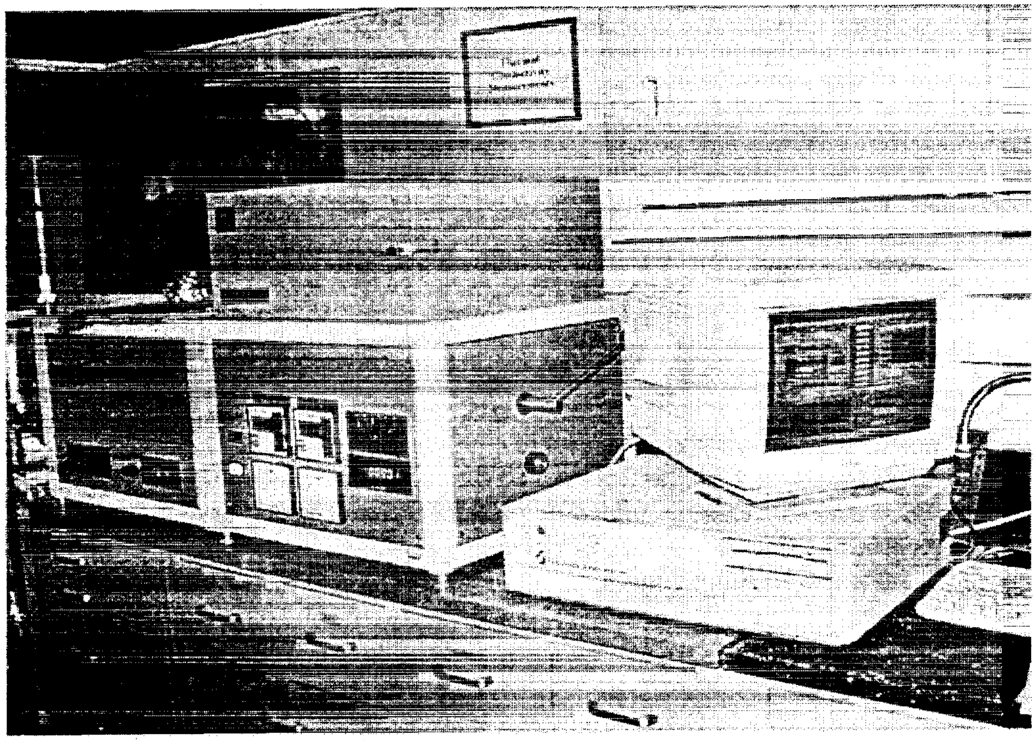

Figure 1 Rapid-k thermal conductivity test apparatus and computer system.

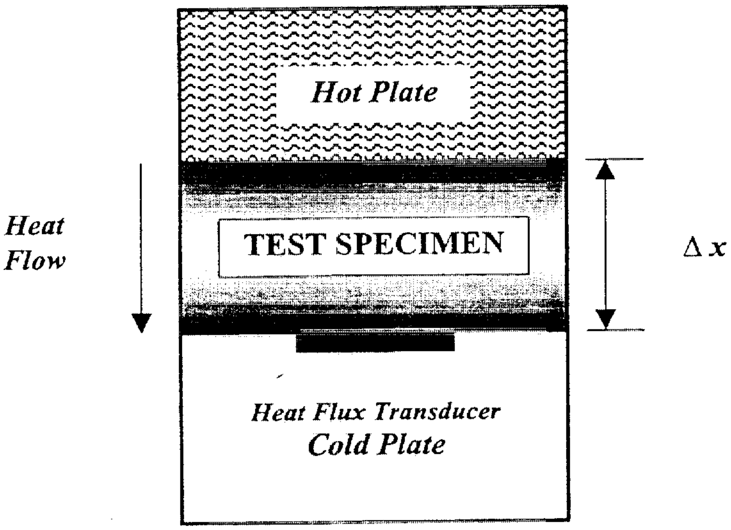

Figure 2 Schematic showing principal of Rapid-k operation.

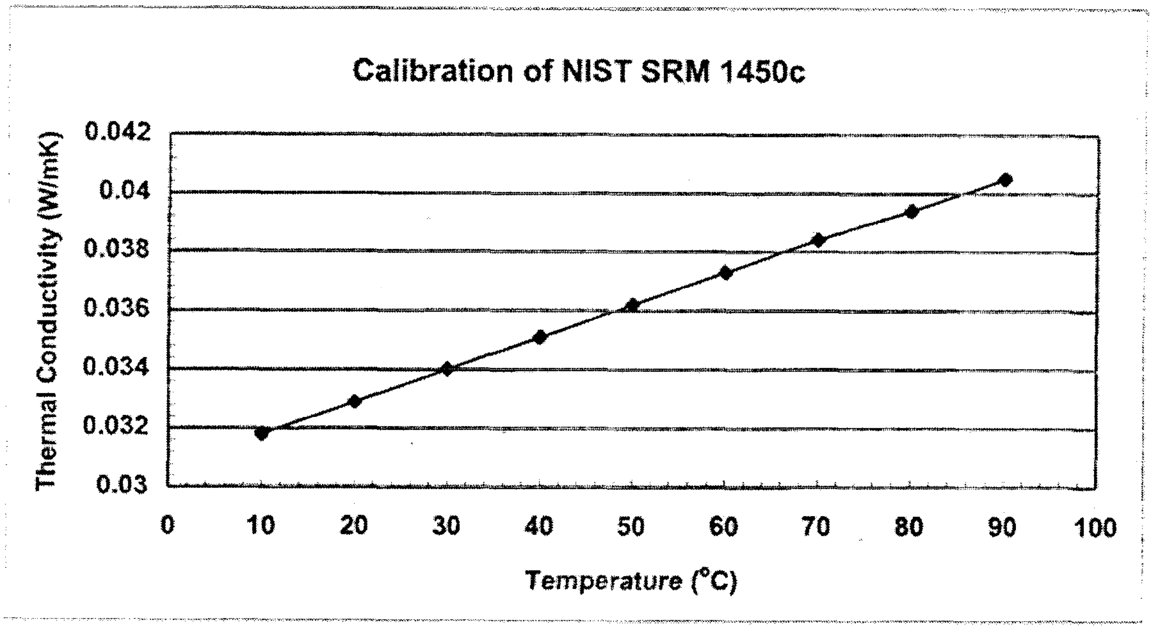

Figure 3 Certified calibration values for SRM 1450c.

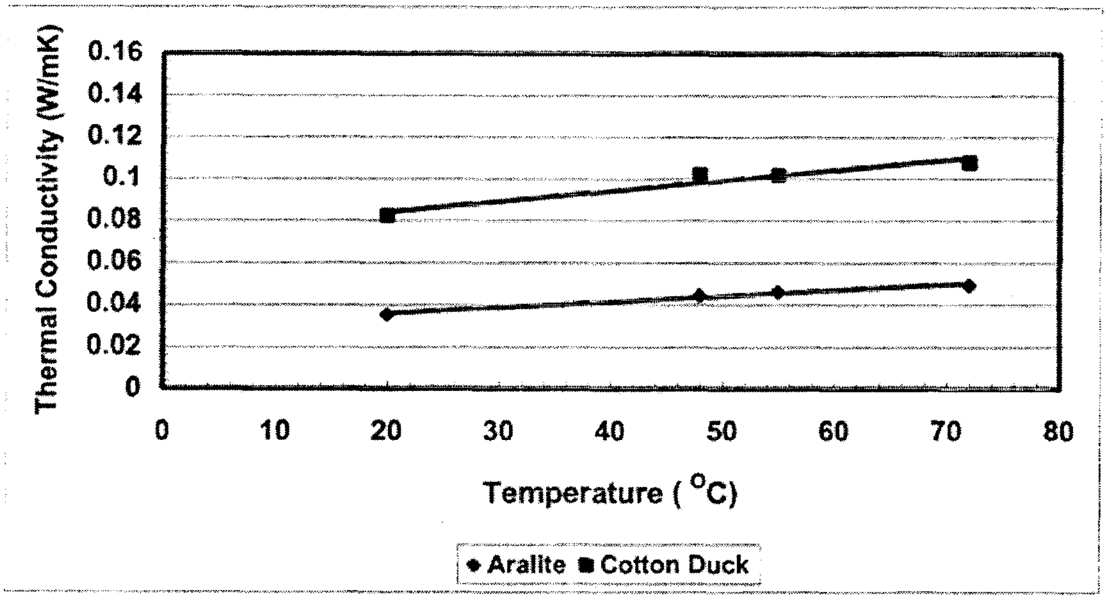

Figure 4 Estimated thermal conductivity for Aralite® and Cotton Duck.

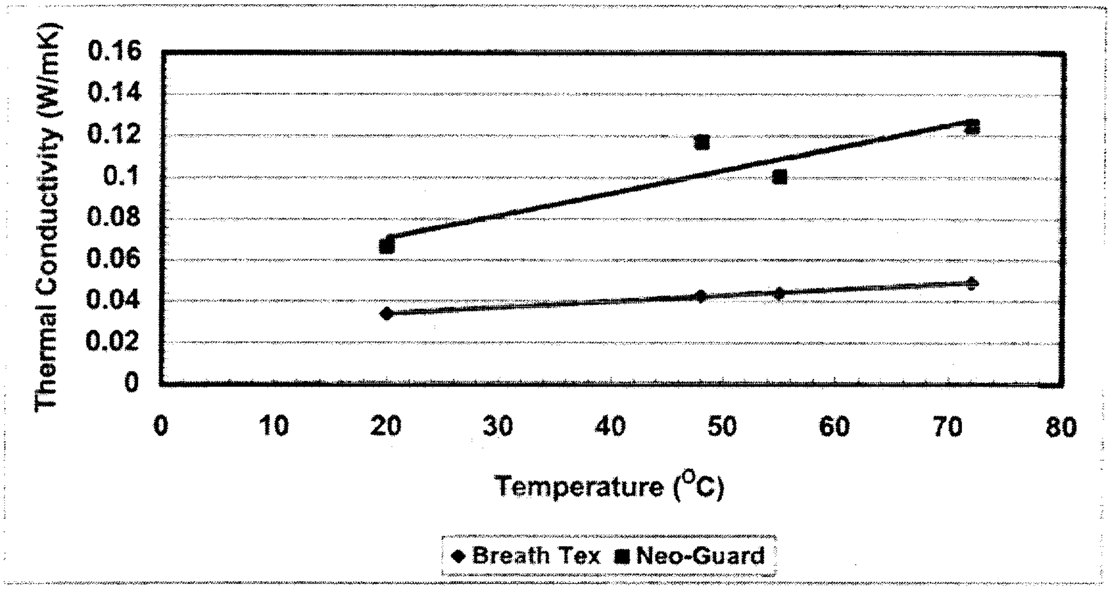

Figure 5 Estimated thermal conductivity for Breath Tex® and Neo-Guard®.

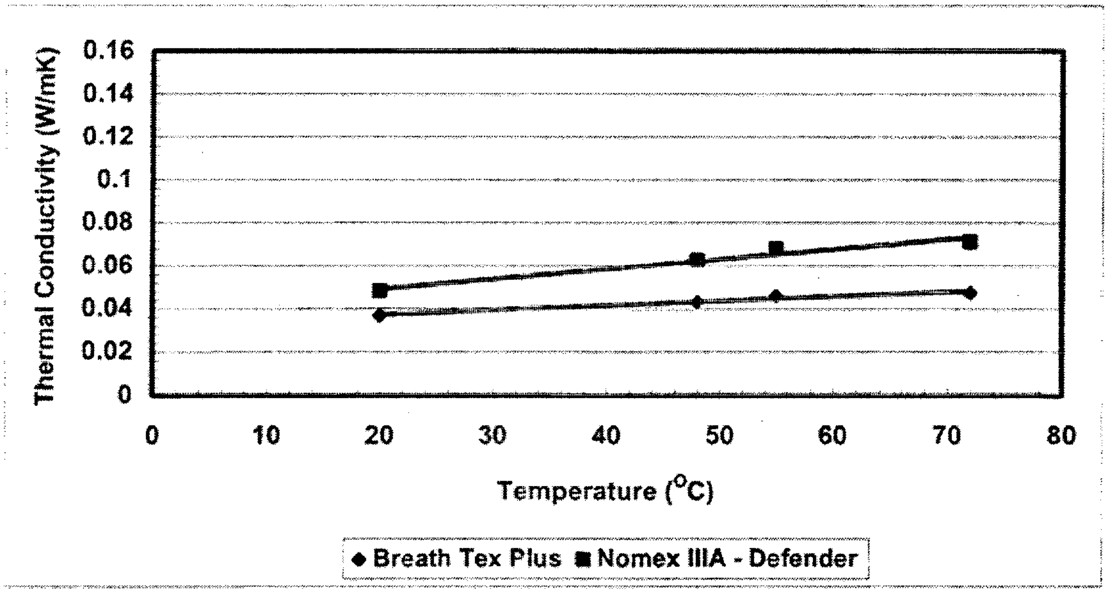

Figure 6 Estimated thermal conductivity for Breath Tex® Plus and Nomex® IIIA-Defender™.

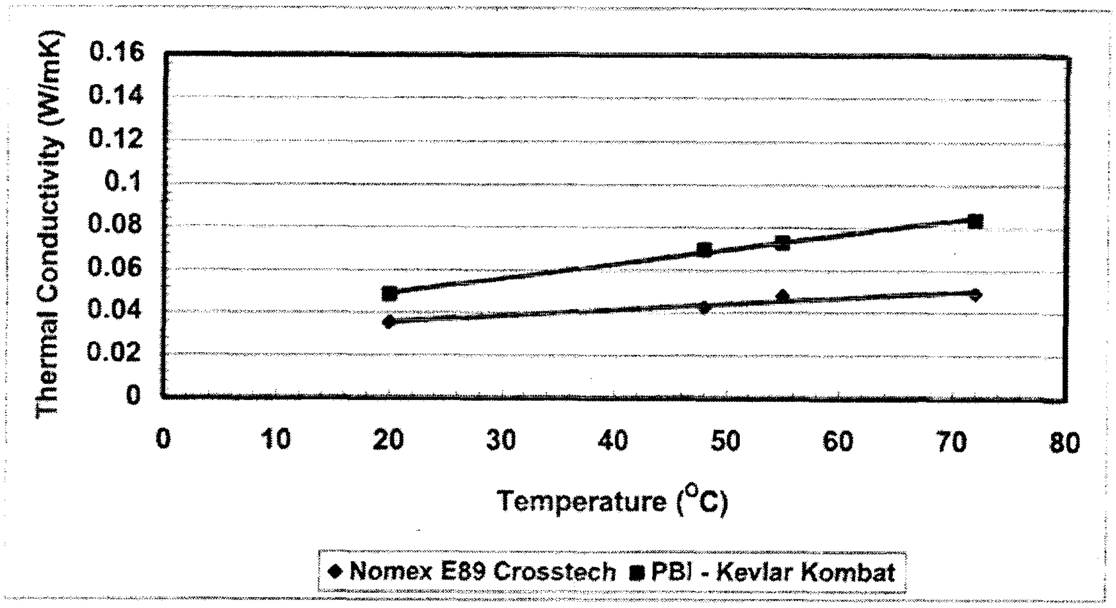

Figure 7 Estimated thermal conductivity for Nomex® E89 Crosstech® and PBI™-Kevlar® Kombat™.

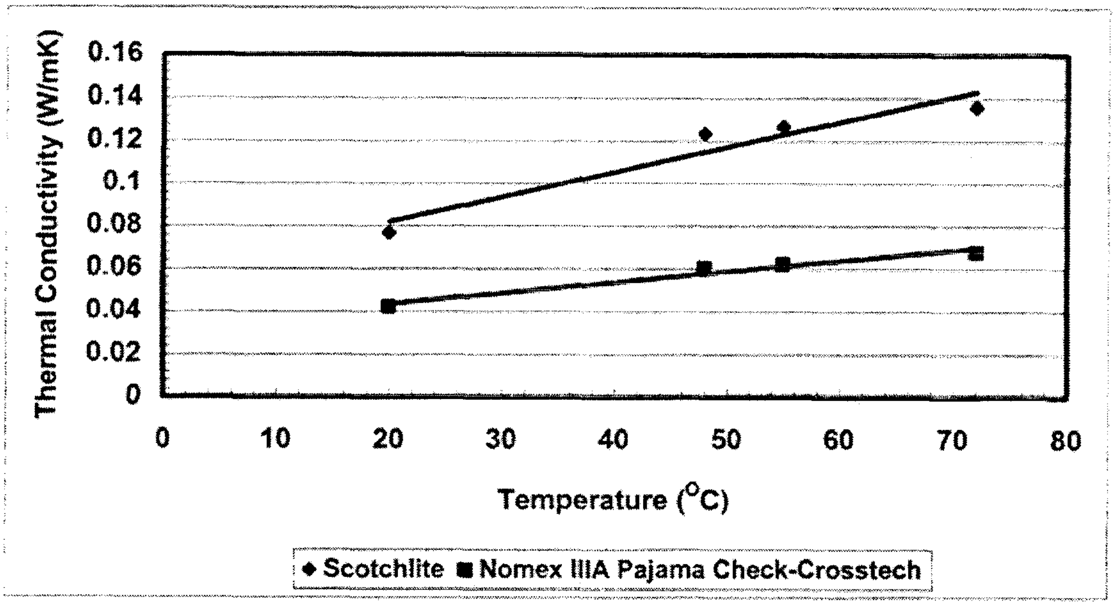

Figure 8 Estimated thermal conductivity for Scotchlite® and Nomex® IIIA Pajama Check–Crosstech®.