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TECHNICAL REPORT
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STANDARDIZATION OF GUARDED HOT PLATE HEAT TRANSFER AND WATER VAPOR PERMEABILITY TESTING AT THREE LABORATORIES

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13. ABSTRACT *(Maximum 200 words)*

Heat transfer and water vapor transport measurements performed at three laboratories using the "sweating" guarded hot plate apparatus were standardized based on the International Organization for Standardization (ISO) International Standard 11092. Comparison testing was conducted on four standard military uniform materials. The adherence to ISO 11092 resulted in good agreement among the three laboratories between measured values of thermal resistance and water vapor resistance for the four materials. The agreement was improved over that seen in a previous study where each laboratory used a different test method.

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PREFACE

This study was conducted to standardize heat transfer and water vapor transport measurements performed by three separate organizations located at the U.S. Army Natick Research, Development and Engineering Center (Natick). The three organizations were the Individual Protection Directorate of Natick, the U.S. Navy Clothing and Textile Research Facility (NCTRF), and the U.S. Army Research Institute of Environmental Medicine (USARIEM).

All NCTRF tests were conducted by Joe Giblo and Donna Windler of the Environmental Sciences Division. The USARIEM tests were conducted by Tom Endrusick of the Biophysics and Biomedical Modeling Division. Phil Gibson of the Textile Research and Engineering Division conducted the Natick tests.

Several people contributed to the success of this study. We appreciate the efforts of Marie Jean-Pierre and Don Schamber of Natick; and Nancy Pimental, Diane Phillips, and Mike Salem of NCTRF. We would especially like to thank Randy Natches and Ken Rowe of the Prototype Fabrication Branch of Natick for building the ductwork required for the test equipment at Natick and NCTRF.

STANDARDIZATION OF GUARDED HOT PLATE HEAT TRANSFER AND WATER VAPOR PERMEABILITY TESTING AT THREE LABORATORIES

1. Introduction

Three organizations located at the U.S. Army Natick Research, Development and Engineering Center (Natick) routinely determine the thermal properties of materials in the laboratory. These organizations are the Survivability Directorate of Natick, the U.S. Army Research Institute of Environmental Medicine (USARIEM), and the U.S. Navy Clothing and Textile Research Facility (NCTRF). All three organizations use a "sweating" guarded hot plate to determine the thermal and water vapor transport properties of materials and evaluate them for their intended use.

A previous report[1] included a comparative study of thermal and water vapor resistance values obtained by each laboratory for two standard materials. The existing test procedures of each laboratory were followed and no attempt was made to standardize test procedures among the three laboratories. The study was performed since there is often a need to compare materials tested at one laboratory with materials tested at another laboratory.

The previous study found that there was generally good agreement between test results, even with the large differences in test procedures between the three laboratories. The interlaboratory results had a consistent bias or offset in measured properties, and the interlaboratory variance was usually within limits quoted in standards for this type of testing. The conclusion of the study was that even greater agreement was possible if all three laboratories followed a standard procedure.

An accepted standard for guarded hot plate testing has recently become available. It is the International Organization for Standardization (ISO) Standard 11092 which covers both heat transfer and water vapor permeability testing[2]. Until the publication of this standard, the only applicable guarded hot plate standards were American Society for Testing and Materials (ASTM) standards[3,4], which only covered dry thermal testing, and the Deutsches Institut für Normung (DIN) 54-101[5], which was a draft German standard upon which the ISO 11092 standard is based.

The test procedures used by USARIEM followed the DIN 54-101 procedures. Since the DIN standard is essentially the same as the ISO standard, USARIEM was already in compliance with the only existing test standard for guarded hot plate testing of thermal and water vapor transport properties. Consequently, both Natick and NCTRF modified their existing equipment to allow testing according to the ISO 11092 standard. With all three laboratories testing to the same standard, test results should agree even more closely than before, which will facilitate interlaboratory comparisons of material properties.

The intent of this present study is to again take a set of standard materials and have them tested by each laboratory. The values for thermal resistance and water vapor permeability obtained by each laboratory are compared, and the interlaboratory variance and offset are determined.

2. Materials and Methods

Materials

Each laboratory was asked to determine the thermal and water vapor transport properties of four different standard materials used in U.S. chemical protective garments. The materials are described and listed below. The sample identification is given in boldface; this identification is the one used in the property tables and charts.

Saratoga
United States Marine Corps Chemical Protective Suit[6]
Outer Layer[7] - 6 oz/yd^2, 100% combed cotton, ripstop poplin weave, Quarpel treated, desert camouflage, Type VI, MIL-C-43468.
Inner Layer[8] - 34 g/m^2 coaxial polyamide/polyester fiber blend nonwoven laminated to 180 g/m^2 Blucher activated carbon spheres, bonded to a polyester tricot knit.

CPO
United States Navy Chemical Protective Overgarment[9]
Outer Layer[10] - Modacrylic/nylon blend twill weave cloth.
Middle Layer[11] - Activated carbon sprayed woven multi-fiber cloth.
Inner Layer[12] - 100% cotton chambray cloth, flame-retardant treated.

BDO
United States Army Battle Dress Overgarment[13]
Outer Layer[14] - 7 oz/yd^2, 50% nylon (type 420, 2.5 denier per filament), 50% carded cotton, twill weave, Quarpel treated, woodland camouflage, Class 2, MIL-C-44031.
Inner Layer[15] - Polyurethane foam impregnated with activated carbon and laminated on the inner side with a nylon tricot knit, MIL-C-43858.

CPU/HWBDU
United States Army Chemical Protective Undergarment[16]
Outer Layer[17] - Hot Weather Battledress Uniform (HWBDU) - 6 oz/yd^2, 100% combed cotton, ripstop poplin weave, desert camouflage.
Inner Layer[18] - Chemical Protective Undergarment (CPU) - Nylon/Lycra tricot fabric containing activated carbon

Three samples of each material were provided to each laboratory. All samples were prepared by personnel at NCTRF. The samples were obtained from previously manufactured suits, cut to size, and then steam pressed to remove wrinkles and to allow them to lay flat.

Methods

The methods used by each laboratory follow those given in ISO 11092, "Measurement of Thermal and Water Vapour Resistance Under Steady-State Conditions (Sweating Guarded-Hotplate Test)". A brief summary of the test method is presented below; for further details refer to ISO 11092.

The guarded hot plate measures the power required to maintain a flat measurement area at a constant temperature. When the plate is covered with a test material, the amount of power required to maintain the plate at a given temperature can be related back to the dry thermal resistance of the test material. If the plate is saturated with water, then the amount of power required to maintain the plate at a given temperature is related to the rate at which water evaporates from the surface of the plate and diffuses through the material. Auxiliary guard heaters are placed around and under the measurement area to insure that heat and water vapor only flow through the measurement area.

Since this method must account for both heat and mass transfer effects, it is necessary to determine the dry thermal resistance of the material first. Then the plate is saturated with water and the material is tested again to determine its water vapor transmission properties.

Air flow over the sample is particularly important since it greatly affects the heat and mass transfer coefficients from the plate. The ISO 11092 Standard calls for a ducted flow over the plate with a turbulence generator at the inlet of the duct. The air speed is specified to be 1 m/s at a point 15 mm above the center of the plate surface. The air velocity coefficient of variation due to turbulence at this point is specified to be between 5% and 10%. The test conditions for the dry plate test and the wet plate test are summarized in Table 1. A list of the specific test equipment, including the guarded hot plate dimensions and manufacturers, is given for each of the three laboratories in Appendix A.

Table 1. ISO 11092 Test Conditions

	Plate Temperature (°C)	Air Temperature (°C)	Air Relative Humidity (%)
Dry Plate Test Conditions	35	20	65
Saturated Plate Test Conditions	35	35	40

Dry Thermal Resistance

Dry thermal resistance of the material is calculated by measuring the temperature difference between the surface of the heated measurement area of the guarded hot plate and the temperature of the ambient air away from the plate. It is this temperature difference which drives heat transfer through the fabric. The equation used for calculating the thermal resistance is:

$$R_{total} = \frac{A(T_{plate} - T_{air})}{Q} \tag{1}$$

R_{total} = Thermal resistance of material plus the boundary air layer (m^2-K/Watt)
A = Surface area of guarded hot plate measurement area (m^2)
T_{plate} = Temperature of the plate surface (°C)
T_{air} = Temperature of the ambient air (°C)
Q = Power required to maintain a constant plate surface temperature (Watt)

The total thermal resistance R_{total} includes the apparent thermal resistance of the boundary air layer above the fabric material surface plus the apparent resistance due to various factors within the apparatus itself. The thermal resistance of apparatus and boundary air layer can be measured by performing a test on the bare plate without a fabric sample. The value of R thus obtained for the bare plate is designated R_{cto}.

R_{cto} decreases as the air speed sweeping over the surface of the guarded hot plate increases. Increased air movement reduces the thickness of the boundary air layer over the plate and enhances heat transfer. Increased turbulence of the air flow also enhances heat transfer from the plate. It is assumed that the boundary air layer over the bare plate is identical to the boundary air layer over the fabric. This assumption may introduce errors if the surface characteristics of the fabric are extremely different from those of the bare plate. The intrinsic thermal resistance R_{ct} of the fabric may be obtained by subtracting out the thermal resistance of the overlying boundary air layer measured during the bare plate test:

$$R_{ct} = R_{total} - R_{cto} \tag{2}$$

The value for R_{ct} is a measure of the intrinsic thermal resistance of the material to dry heat transfer, and the same value of R_{ct} should be obtained by each laboratory for a given material.

Water Vapor Resistance

The water vapor resistance of a material is analogous to the dry thermal resistance of the material. The guarded hot plate can be saturated with water so that its surface is completely wet. A thin saturated cellophane film placed over the plate surface prevents liquid water from wicking into the fabric, yet allows water to freely pervaporate through the film. The power required to maintain the plate surface at a given temperature is related to the rate at which water evaporates from the surface of the plate and diffuses through the test material. The ISO 11092 test conditions call for no temperature difference between the ambient air and the plate surface. In this case, the driving force for energy transfer through the test material is not a temperature difference, but a vapor pressure difference between the saturated plate surface and the ambient air.

The equation used for calculating the water vapor resistance is:

$$R_{etotal} = \frac{A(p_s - \phi p_a)}{Q} \tag{3}$$

R_{etotal} = Water vapor resistance of material plus the boundary air layer (m^2-Pa/Watt)
A = Surface of guarded hot plate measurement area (m^2)
p_s = Saturated water vapor pressure at the plate surface (Pa)
p_a = Saturated water vapor pressure of the ambient air (Pa)
Q = Power required to maintain a constant plate surface temperature (Watt)
ϕ = Relative humidity of the ambient air (fractional)

The intrinsic water vapor resistance R_{et} of the fabric may be determined by subtracting out the value of the water vapor resistance measured for the bare plate, R_{eto}:

$$R_{et} = R_{etotal} - R_{eto} \tag{4}$$

Intrinsic Water Vapor Permeability Index

The values for R_{ct} and R_{et} may be combined to give an efficiency factor of the material compared to an air layer of the same thickness:

$$i_{mt} = S\frac{R_{ct}}{R_{et}} \tag{5}$$

i_{mt} = intrinsic water vapor permeability index (dimensionless)
S = Lewis Constant (60 Pa/K)
R_{ct} = Intrinsic thermal resistance (m^2-K/W)
R_{et} = Intrinsic water vapor resistance (m^2-Pa/W)

Conversion to Other Quantities

The quantities R_{ct}, R_{et}, and i_{mt} may be easily converted to some of the more traditional units often used in clothing evaluation. For convenience the conversions to clo and i_m are given below; further information on the conversion equations may be found in Reference 19.

$$clo = \left\{ 6.461 \frac{clo}{\left(\frac{m^2 - K}{Watt} \right)} \right\} (R_{ct}) \tag{6}$$

$$i_m = \left(60 \frac{Pa}{K} \right) \left\{ \frac{R_{ct} + R_{cto}}{R_{et} + R_{eto}} \right\} \tag{7}$$

3. Results and Discussion

All test results are tabulated in Appendix B. The results for each sample are given, as well as the averages, sample variance, and sample deviation. The comparisons discussed later are based on the calculated averages from the tables in Appendix B.

The results for the four materials are shown in Figures 1 and 2. The error bars refer to the coefficient of variance measured on the three samples tested by each laboratory.

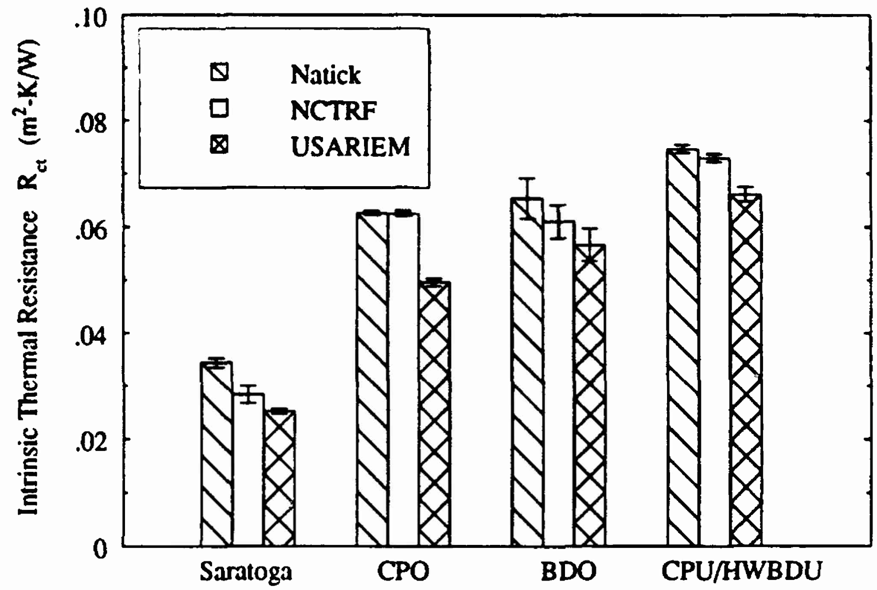

Figure 1. Thermal Resistance of Four Materials as Measured by Three Different Laboratories.

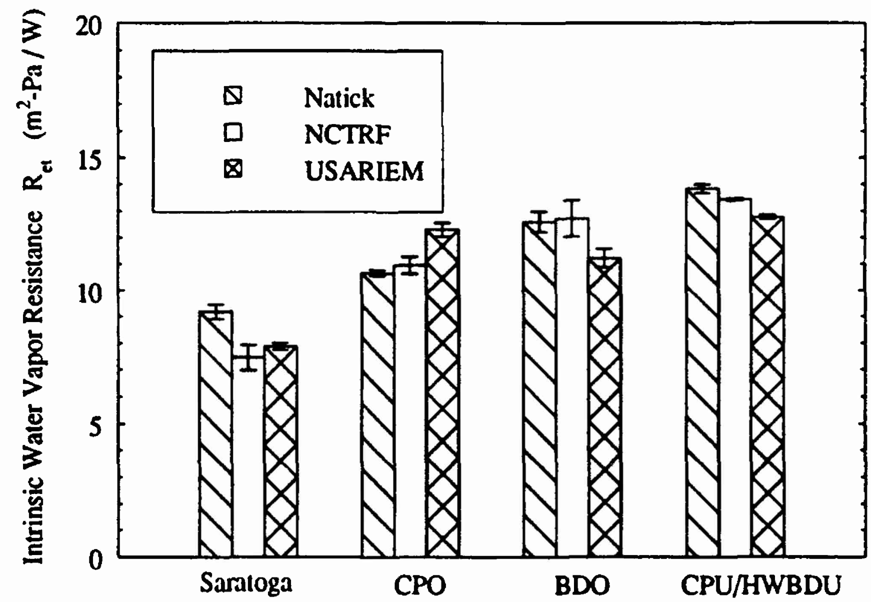

Figure 2. Water Vapor Resistance of Four Materials as Measured by Three Different Laboratories.

All three labs seem to agree fairly well. The agreement between the results has been improved over that seen in the previous comparison where each laboratory used a different test method.

The offset between laboratories does not seem to be very consistent. This may be due to inherent differences in the test equipment, and the many small variations in the individual test procedures of the three laboratories. For example, each laboratory may have differed in how the fabric sample was placed on the plate. Labs which smoothed the materials on the plate with heavy pressure would show different results than labs which just let the materials lie naturally on the plate.

The question arises whether the test results in Figures 1 and 2 show good agreement or not. Each laboratory did not test identical samples, which is the usual case in a round-robin testing arrangement, but tested different samples of the same material. The test results thus include both between-laboratory variation plus the variability of the material itself. Within each laboratory the sample-to-sample variability is very low for all the materials except the BDO, which, due to variations in thickness and weight, had quite a large variance in measured properties for all three laboratories.

ISO 11092 contains guidelines for interlaboratory variation. An interlaboratory trial involving 4 laboratories, using three samples each of a foam material formed in three different thicknesses, found an average standard deviation of 6.5×10^{-3} m^2-K/W for thermal resistance R_{ct} and an average standard deviation of 0.67 m^2-Pa/W for water vapor resistance R_{et}. It is important to note that these laboratories all used the same samples, not different samples cut from the same lot of material. The interlaboratory trial also involved guarded hot plates made by the same manufacturer.

In our study, the comparable average standard deviation for the three laboratories for the value of thermal resistance R_{ct} was 6.1×10^{-3} m^2-K/W. The average standard deviation for the value of water vapor resistance R_{et} was 0.91 m^2-Pa/W. This thermal resistance value is within the range found in the interlaboratory trial contained in ISO 11092, while the water vapor resistance value is slightly higher. This is very encouraging, especially considering that there are some differences in the plate design between Natick, USARIEM, and NCTRF, and that the three laboratories did not test the same samples.

There are specific analysis methods which have been developed to characterize the statistical quantities of test precision, repeatability, and bias involved in interlaboratory test results. The ASTM publishes several applicable analysis methods, contained in References 20-23. These methods make it possible to separate the causes of test result variability into such factors as material variance, operator bias, measurement error, etc.

Such a detailed analysis is not presented here, although a statistician could perform this type of analysis with the data contained in Appendix B. The interlaboratory variance and offset will be calculated in a much simpler way as described below.

The global average is taken to be the average of all laboratory results for an individual material. This set of test measurements is also used to calculate the global coefficient of variance. The individual laboratory offset is defined as the difference between the laboratory average for the material and the global average. Further details on the calculations for each material are presented in Appendix C.

It is often the case in interlaboratory test comparisons that the offset may vary with the intrinsic properties of the material. To see if this is true, the observed absolute offset from the global average against the thermal or water vapor resistance may be plotted, as shown in Figures 3 and 4. We see that there is no clear relation between the sample level of resistance and the measured interlaboratory offset from the global average.

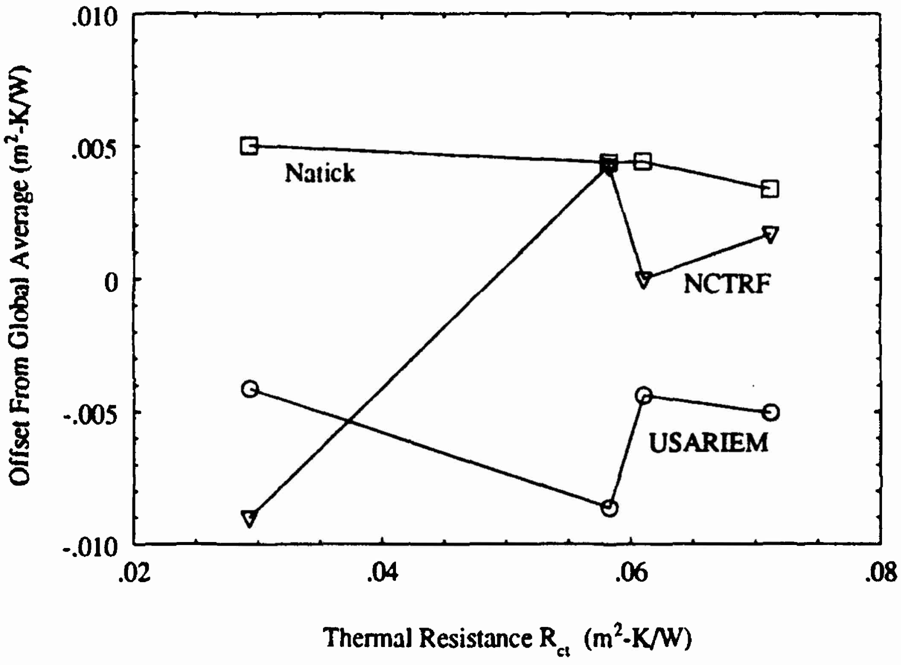

Figure 3. Individual Laboratory Offset From Global Average as Function of Sample Property Level for Thermal Resistance R_{ct} (Data from Appendix C).

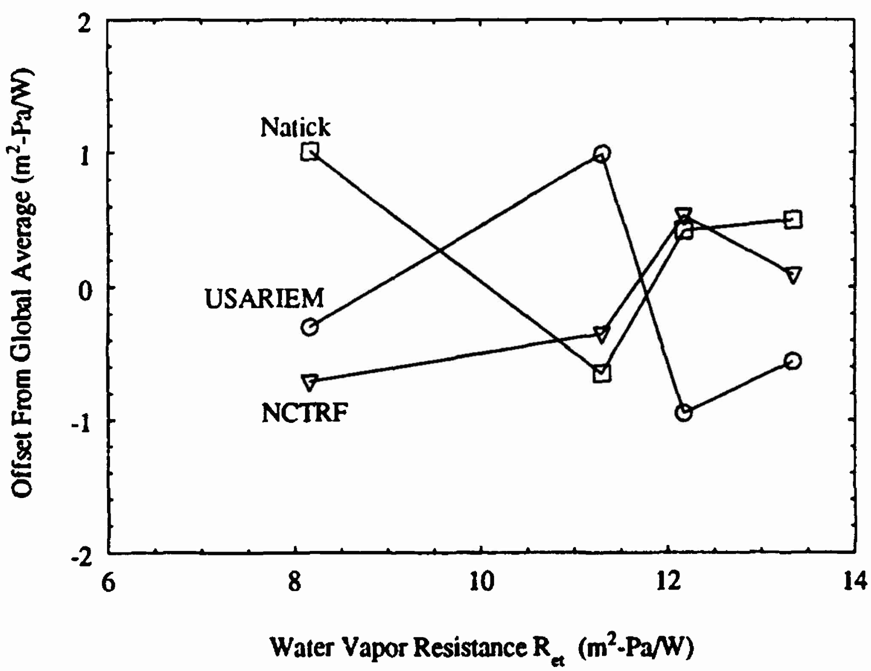

Figure 4. Individual Laboratory Offset From Global Average as Function of Sample Property Level for Water Vapor Resistance R_{et} (Data from Appendix C).

This interlaboratory offset from a global average can be used to correct the data from different laboratories. Each laboratory applies the offset to its calculated average to get a corrected average. This could be useful when all three laboratories are trying to compare data generated on different materials.

We can apply the offset correction to the data from each laboratory and calculate the new global averages and global standard deviation. We may also calculate 95% confidence limits for the corrected data. Figures 5 and 6 show the data from each laboratory corrected for average offset from the global average. By applying the offset correction, the average standard deviation for the dry thermal resistance decreased to 3.3 x 10^{-3} m^2-K/W, which corresponds to an average coefficient of variation of about 0.06 or 6%. The average standard deviation for the water vapor resistance decreased to 0.81 m^2-Pa/W, which corresponds to a coefficient of variation of about 0.08 or 8%.

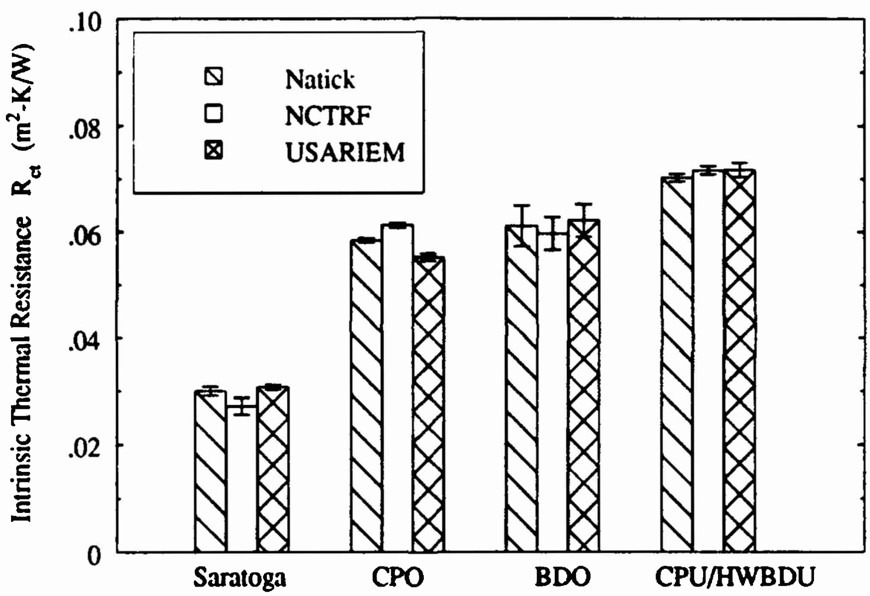

Figure 5. Thermal Resistance of Four Materials Corrected for Offset From Global Average.

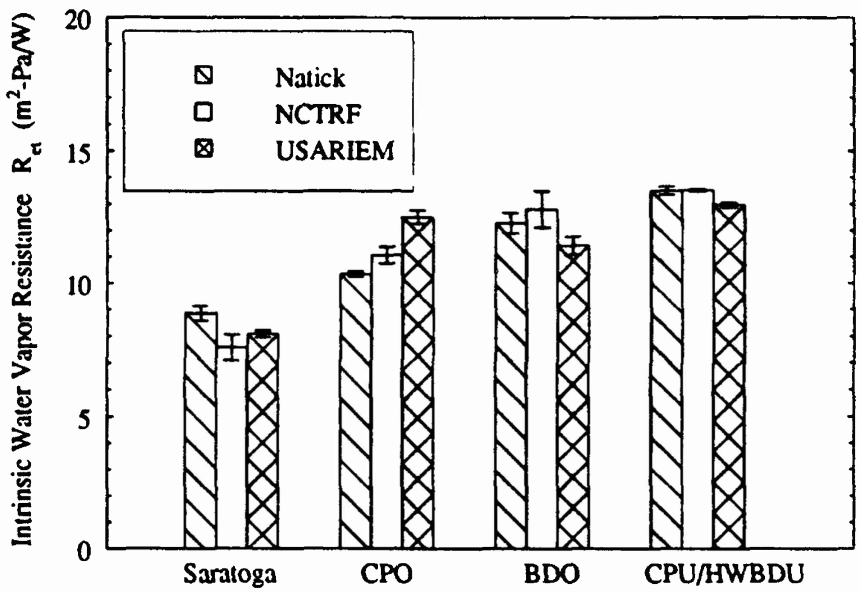

Figure 6. Water Vapor Resistance of Four Materials Corrected for Offset From Global Average.

The 95% confidence limits for the measured properties of R_{ct} and R_{et} for each material are shown in Figures 7 and 8. The confidence limits are calculated based on the expected average offset for each lab and applied to the global averages which are corrected for each laboratory's offset (see Appendix C).

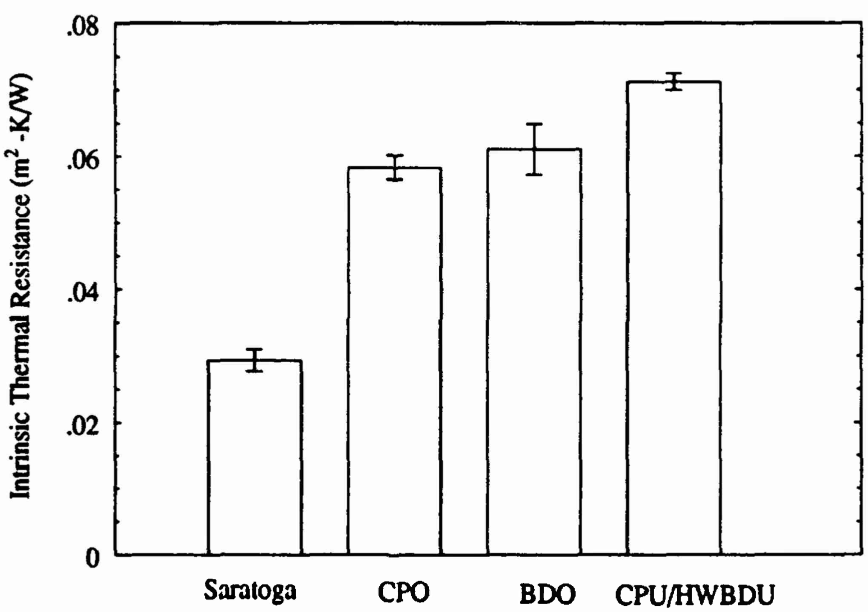

Figure 7. 95% Confidence Limits of Thermal Resistance for Four Materials
Applied to Global Averages From Three Laboratories

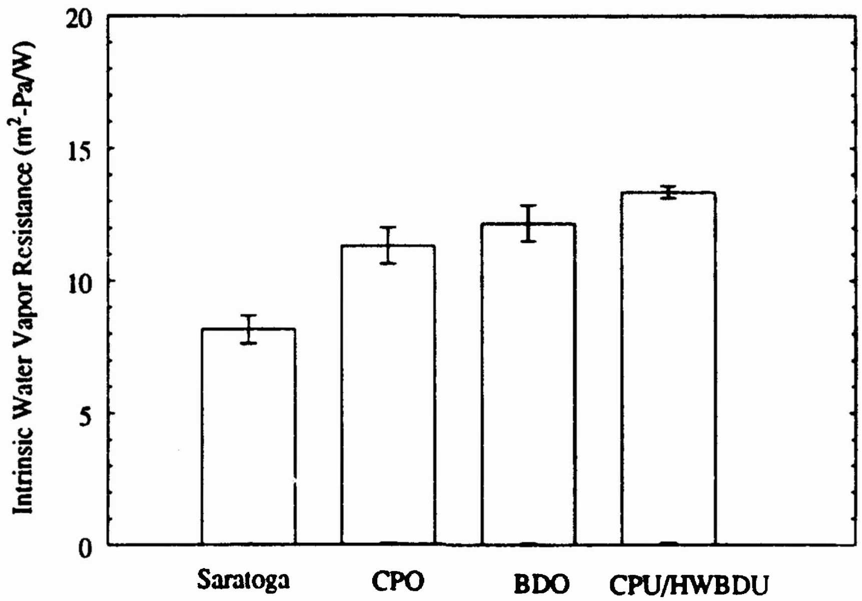

Figure 8. 95% Confidence Limits of Water Vapor Resistance for Four Materials Applied to Global Averages From Three Laboratories

Although we do see some improvement, the use of the *offset correction factors* derived here does not reduce the average coefficient of variation of these materials by more than 5% for either thermal or water vapor resistance values. The use of the correction factor derived here is probably not justified since the improvement in interlaboratory agreement is so minimal, and is comparable in magnitude to the variability of results due to material variability and the test method itself.

4. Conclusions

The use of the ISO 11092 test standard improved the agreement between three different laboratories for measured values of thermal resistance and water vapor resistance for several textile materials.

The average standard deviation for the interlaboratory results is comparable to that obtained for other interlaboratory comparisons which used identical test samples and test apparatus. This is excellent considering that for our testing there were extra sources of variability present. One source of variability was due to the test equipment design itself, since not all three laboratories used test equipment made by the same manufacturer. Another extra source of variability was due to the large differences in some of the test samples, especially the BDO material, which had a variation in material properties of around 10%.

A correction factor was derived based on the average standard deviation for each laboratory. This correction factor was applied to data generated at each laboratory. The correction factor slightly improved the agreement between laboratories, but the improved agreement is not significant enough to justify the use of the correction factor in analyzing data generating at the different laboratories. Even without a correction factor, for materials with little inherent variability from sample to sample, interlaboratory agreement should be on the order of 5% for both thermal and water vapor resistance values.

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5. Deutsches Institut für Normung (DIN) Draft Standard 54-101, Measurement of Stationary Thermal and Water Vapour Resistance by Means of a Thermoregulatory Model of Human Skin (1984).

6. Military Specification, MIL-S-29461, Suit, Chemical and Biological Protective (Carbon Sphere), Class 2 - Desert Camouflage Printed.

7. Military Specification, MIL-C-43468, Cloth, Camouflage Pattern, Wind Resistant Poplin, Cotton, Type VI, Quarpel Treated.

8. Military Specification, MIL-C-29462, Cloth, Laminated, Polyester Tricot Knit, Activated Carbon Sphere, Chemical Protective.

9. Purchase Description, NCTRF/PD 10-84A, Suit, Chemical Protective.

10. Ministry of Defence Specification, United Kingdom, UK/SC/3938C, Cloth, Twill, Modacrylic and Nylon.

11. Ministry of Defence Specification, United Kingdom, UK/SC/3346G, Cloth, Bonded, Multi-Fibre, Anti-gas.

12. Military Specification, MIL-S-24916A, Cloth, Chambray, Cotton (Flame-Retardant Treated).

13. Military Specification, MIL-S-43926H, Suit, Chemical Protective, Class 1-Woodland Camouflage.

14. Military Specification, MIL-C-44031D, Cloth, Camouflage pattern: Woodland, Cotton and Nylon, Class 2 - Camouflage Printed and Quarpel Treated.

15. Military Specification, MIL-C-43858B(GL), Cloth, Laminated, Nylon Tricot Knit,

Polyurethane Foam Laminate, Chemical Protective and Flame Resistant, Type III.

16. Military Specification, MIL-U-44435(GL), Underwear, Chemical Protective, Two Piece (Undershirt and Drawers).

17. Military Specification, MIL-C-43468, Cloth, Camouflage Pattern, Wind Resistant Poplin, Cotton, Type III.

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APPENDICES

APPENDIX A

Test Equipment

U.S. Army Natick Research, Development and Engineering Center (Natick)

Plate Manufacturer:	Dynatech R/D Company (reorganized as Holometrix, Inc.)
Plate Dimensions:	Measurement Area = 0.0645 m^2 Guard Area = 0.1935 m^2
Chamber Manufacturer:	Tenney Engineering, Inc.
Chamber Volume:	0.84 m^3
Anemometer Type:	Hot-Wire Anemometer, Tri-Sense Model 37000-00, Cole-Parmer Instrument Co. or Thermal-Ball Anemometer, Testo 452, Testoterm GmbH & Co (Germany).

U.S. Navy Clothing and Textile Research Facility (NCTRF)

Plate Manufacturer:	Dynatech R/D Company (reorganized as Holometrix, Inc.)
Plate Dimensions:	Measurement Area = 0.0645 m^2 Guard Area = 0.1935 m^2
Chamber Manufacturer:	Envirotronics, Inc.
Chamber Volume:	0.84 m^3
Anemometer Type:	Hot-Wire Anemometer, Model 415-3, Kurz Instruments, Inc.

U.S. Army Research Institute of Environmental Medicine (USARIEM)

Plate Manufacturer:	Hohenstein Institute (Federal Republic of Germany)
Plate Dimensions:	Measurement Area = 0.040 m^2 Guard Area = 0.104 m^2 Note - Guard area is <u>not saturated</u> during a vapor permeability test
Chamber Manufacturer:	Weiss Umwelttechnik, GMBH (Federal Republic of Germany)
Chamber Volume:	0.64 m^3
Anemometer Type:	Hot-Wire Anemometer, Alnor Compuflow, Model GGA-65P Thies Clima Co. (Germany)

APPENDIX B

Thermal Property Data

Table B-1. Natick Thermal Property Data

Material	Sample #	Thermal Resistance R_{ct} (m^2-K/W)	Water Vapor Resistance R_{et} (m^2-Pa/W)	Water Vapor Permeability Index i_{mt}
Saratoga	25A/B	0.0328	9.53	0.21
	26A/B	0.0362	9.46	0.23
	27A/B	0.0341	8.54	0.24
	Average	**0.0344**	**9.18**	**0.23**
	Standard Deviation	0.0017	0.552	0.017
	Coefficient of Variance	0.050	0.060	0.075
CPO	19A/B/C	0.0618	10.40	0.36
	20A/B/C	0.0627	10.74	0.35
	21A/B/C	0.0635	10.81	0.35
	Average	**0.0626**	**10.65**	**0.35**
	Standard Deviation	0.0009	0.219	0.003
	Coefficient of Variance	0.014	0.021	0.009
BDO	31A/B	0.0571	11.70	0.29
	32A/B	0.0720	13.02	0.33
	33A/B	0.0672	13.05	0.31
	Average	**0.0654**	**12.59**	**0.31**
	Standard Deviation	0.0076	0.771	0.019
	Coefficient of Variance	0.116	0.061	0.063
CPU/ HWBDU	13/13A	0.0754	14.20	0.32
	14/14A	0.0755	13.70	0.33
	15/15A	0.0728	13.60	0.32
	Average	**0.0746**	**13.83**	**0.33**
	Standard Deviation	0.0016	0.321	0.007
	Coefficient of Variance	0.021	0.023	0.021

Bare Plate R_{cto} = 0.0548 m^2-K/W
Bare Plate R_{eto} = 5.0 m^2-Pa/W

Table B-2. NCTRF Thermal Property Data

Material	Sample #	Thermal Resistance R_{ct} (m^2-K/W)	Water Vapor Resistance R_{et} (m^2-Pa/W)	Water Vapor Permeability Index i_{mt}
Saratoga	28A/B	0.0310	7.74	0.24
	29A/B	0.0295	8.23	0.22
	30A/B	0.0248	6.39	0.23
	Average	**0.0284**	**7.45**	**0.23**
	Standard Deviation	0.0032	0.953	0.013
	Coefficient of Variance	0.114	0.128	0.057
CPO	22A/B/C	0.0620	11.30	0.33
	23A/B/C	0.0636	11.34	0.34
	24A/B/C	0.0620	10.21	0.36
	Average	**0.0625**	**10.95**	**0.34**
	Standard Deviation	0.0009	0.641	0.019
	Coefficient of Variance	0.015	0.059	0.054
BDO	34A/B	0.0543	11.60	0.28
	35A/B	0.0620	12.27	0.30
	36A/B	0.0667	14.25	0.28
	Average	**0.0610**	**12.71**	**0.29**
	Standard Deviation	0.0063	1.378	0.013
	Coefficient of Variance	0.103	0.108	0.045
CPU/ HWBDU	16/16A	0.0713	13.33	0.32
	17/17A	0.0744	13.42	0.33
	18/18A	0.0729	13.52	0.32
	Average	**0.0729**	**13.42**	**0.33**
	Standard Deviation	0.0016	0.095	0.006
	Coefficient of Variance	0.021	0.007	0.020

Bare Plate R_{cto} = 0.0512 m^2-K/W
Bare Plate R_{eto} = 4.0 m^2-Pa/W

Table B-3. USARIEM Thermal Property Data

Material	Sample #	Thermal Resistance R_{ct} (m^2-K/W)	Water Vapor Resistance R_{et} (m^2-Pa/W)	Water Vapor Permeability Index i_{mt}
Saratoga	1A/B	0.0243	8.16	0.18
	2A/B	0.0250	7.72	0.19
	3A/B	0.0263	7.70	0.20
	Average	**0.0252**	**7.86**	**0.19**
	Standard Deviation	0.0010	0.260	0.013
	Coefficient of Variance	0.040	0.033	0.069
CPO	7A/B/C	0.0512	11.72	0.26
	8A/B/C	0.0491	12.68	0.23
	9A/B/C	0.0486	12.48	0.23
	Average	**0.0496**	**12.29**	**0.24**
	Standard Deviation	0.0014	0.506	0.017
	Coefficient of Variance	0.028	0.041	0.069
BDO	4A/B	0.0604	10.53	0.34
	5A/B	0.0495	11.19	0.26
	6A/B	0.0600	11.94	0.30
	Average	**0.0566**	**11.22**	**0.30**
	Standard Deviation	0.0062	0.705	0.039
	Coefficient of Variance	0.109	0.063	0.013
CPU/ HWBDU	10/10A	0.0659	12.64	0.31
	11/11A	0.0690	12.95	0.32
	12/12A	0.0635	12.68	0.30
	Average	**0.0661**	**12.76**	**0.31**
	Standard Deviation	0.0028	0.169	0.010
	Coefficient of Variance	0.042	0.013	0.031

Bare Plate R_{cto} = 0.0595 m^2-K/W
Bare Plate R_{eto} = 4.9 m^2-Pa/W

APPENDIX C

Statistical Averages and Laboratory Offsets

Definitions:

n = number of samples

x = individual sample value

Average value for n samples = $\bar{x} = \frac{\sum x}{n}$

Standard Deviation (unbiased) = $\sigma = \sqrt{\frac{n\sum x^2 - \left(\sum x\right)^2}{n(n-1)}}$

Coefficient of Variation = $\frac{\sigma}{\bar{x}}$

95% Confidence Interval = $\bar{x} \pm 1.96\left(\frac{\sigma}{\sqrt{n}}\right)$

The *Global Average* is calculated as the average of all 9 measured values of R_{ct} or R_{et} obtained by each laboratory. All 9 of these values are also used to obtain the *Global Standard Deviation* and the *Global Coefficient of Variance* for each material.

The *Offset From Global Average* is calculated from the difference between the *Global Average* and the individual material average obtained by each laboratory. The average offset for each laboratory is then the average of the offsets obtained for each material. The individual material and laboratory offsets, together with the average offsets, are shown in Tables C-1 and C-2.

Table C-1. Offset From Global Average for Thermal Resistance R_{ct} (m^2-K/W).

	Saratoga	CPO	BDO	CPU/HWBDU	Average Offset
Natick	0.00503	0.00439	0.00441	0.00338	0.00430
NCTRF	-0.00090	0.00426	-0.00002	0.00168	0.00125
USARIEM	-0.00413	-0.00864	-0.00439	-0.00506	-0.00556

Table C-2. Offset From Global Average for Water Vapor Resistance R_{et} (m^2-Pa/W).

	Saratoga	CPO	BDO	CPU/HWBDU	Average Offset
Natick	1.02	-0.65	0.42	0.50	0.320
NCTRF	-0.71	-0.35	0.53	0.09	-0.109
USARIEM	-0.30	0.99	-0.95	-0.56	-0.210

We can apply the average offset to the individual sample data obtained by each laboratory. If we do this we can obtain a new global average, standard deviation, and coefficient of variance for each material. We may also use the standard deviation to obtain 95% confidence limits for the global averages for each material. If we then average these quantities across the four materials we can get an estimate of the average standard deviation, average coefficient of variation, and the average 95% confidence limits we might expect for a typical material. These quantities are shown in Tables C-3 and C-4.

Table C-3. Global Statistics After Offsets are Applied to Individual Laboratory Data for Thermal Resistance (m^2-K/W)

				95% Confidence Interval		
	Global Average	Standard Deviation	Coefficient of Variance	$1.96\sigma / \sqrt{N}$	Low	High
Saratoga	0.02933	0.0025	0.0856	0.00164	0.0277	0.0310
CPO	0.05828	0.0028	0.0480	0.00182	0.0565	0.0601
BDO	0.06102	0.0059	0.0968	0.00386	0.0572	0.0649
CPU/HWBDU	0.07119	0.0019	0.0265	0.00123	0.0700	0.0724
Averages		0.0032	0.0642	0.00214		

Table C-4. Global Statistics After Offsets are Applied to Individual Laboratory Data for Water Vapor Resistance (m^2-Pa/W)

				95% Confidence Interval		
	Global Average	Standard Deviation	Coefficient of Variance	$1.96\sigma / \sqrt{N}$	Low	High
Saratoga	8.16	0.7995	0.0979	0.5223	7.64	8.68
CPO	11.30	1.0471	0.0927	0.6841	10.61	11.98
BDO	12.17	1.0551	0.0867	0.6893	11.48	12.86
CPU/HWBDU	13.34	0.3356	0.0252	0.2193	13.12	13.56
Averages		0.8093	0.0756	0.5287		

APPENDIX D

Factors Affecting Accuracy of ISO 11092 Method

There are several factors which may affect the accuracy of the ISO 11092 test method. The most important of these is the way in which the boundary air layers caused by the air flow over the plate interact with the thermal guard system used for the guarded hot plate.

A schematic of a typical guarded hot plate is shown below in Figure D-1. The guard and bucking heaters shown are maintained at the same temperature as the center measurement section. This ensures that heat only flows upward through the measurement section. The amount of power needed to maintain the center measurement section at a constant temperature is thus related only to various constant resistance factors within the plate itself, plus the thermal resistance of the test sample and the overlying boundary air layer.

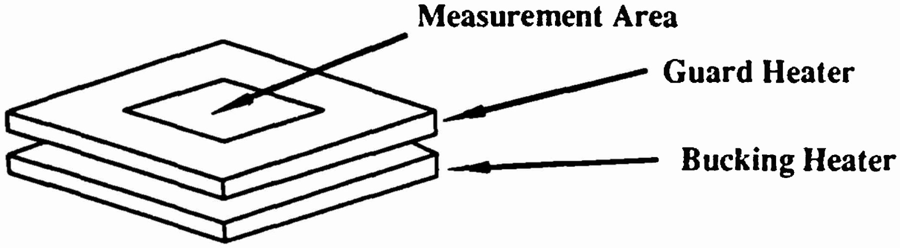

Figure D-1. Schematic of Guarded Hot Plate Apparatus.

The principles of the guarded hot plate assume that the temperature distribution is symmetrical with respect to the center of the measurement area. The guard and bucking heater power levels are controlled to keep the average temperature difference of thermopiles, located at the boundary between the different plates, as close to zero as possible.

If the temperature distribution is not symmetrical with respect to the plate center, the controllers may still be able to set power levels so that the thermopile output is zero, but there may now be a temperature difference between one part of the plate and another, which means some heat may be flowing from the plate measurement area to the thermal guard area and not through the test specimen.

The ISO 11092 test method produces a nonsymmetrical temperature distribution across the guarded plate due to the turbulent ducted flow specified in the test conditions. At the duct entrance, boundary layer growth begins. The boundary layer grows along the plate length up to the duct exit. This type of flow implies that although the plate surface should ideally be at 35°C, it actually varies in the direction of the air flow. This is shown schematically in Figure D-2.

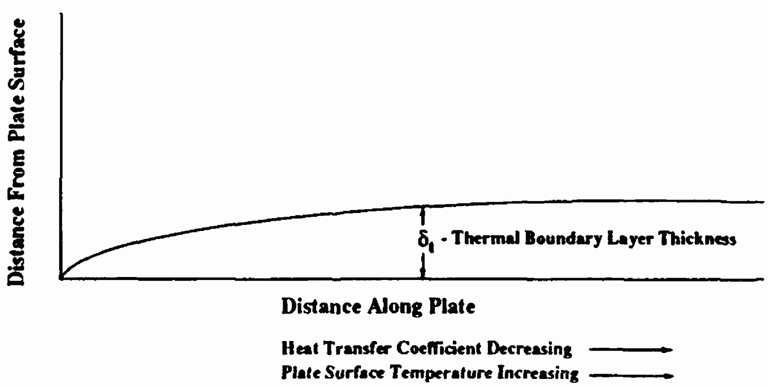

Figure D-2. Boundary Layer Growth Along the Guarded Hot Plate.

This variation in temperature along the plate surface could cause errors in the measured properties of materials. It is difficult to estimate what the possible error is since the free stream flow has a significant level of turbulence. Several references[24,25] allow one to predict temperature distributions and heat transfer coefficients along a flat plate in laminar air flow, but little has been done for a flow with significant amounts of turbulence. One research group in Japan[26] has investigated the effect of free stream turbulence on flat plate transfer, and we can use their results to estimate how much the heat transfer coefficient will vary across the length of the plate.

For a level of turbulence between 5% and 10%, the Nusselt number (**Nu**) can be related to the Reynolds number (**Re**) as:

$$\mathbf{Nu}_x = 0.0291\mathbf{Re}_x^{\;0.8}$$

where $\mathbf{Nu}_x = \dfrac{\bar{h}_x L}{k}$ and $\mathbf{Re}_x = \dfrac{U_0 \rho L}{\mu}$

$\bar{h}_x$ = average heat transfer coefficient $\left(\dfrac{\mathrm{W}}{\mathrm{m}^2-{}^\circ\mathrm{C}}\right)$

L = distance along the plate (m)

k = air thermal conductivity = $0.02723 \left(\dfrac{\mathrm{W}}{\mathrm{m}-{}^\circ\mathrm{C}}\right)$

U_0 = air velocity = 1 m/s

ρ = air density = 1.175 kg/m^3

μ = air intrinsic viscosity = $1.9\mathrm{x}10^{-5}\left(\dfrac{\mathrm{kg}}{\mathrm{m}-\mathrm{s}}\right)$

We may write an expression for the local average heat transfer coefficient in terms of the distance L (in meters) along the plate as:

$$\bar{h}_x = \left(\frac{7.9\times10^{-4}}{L}\right)(61840L)^{0.8}$$

If we pick two locations on the plate which correspond to the boundaries between the measurement area and the guard area we may get an idea of the difference in heat transfer coefficient between the two locations. If we use the Natick plate as an example, the two values for L are 0.127 m and 0.381 m. The corresponding heat transfer coefficients are 8.1 W/m^2-°C and 6.5 W/m^2-°C. These two numbers represent the average heat transfer coefficient from the beginning of the plate to that point. The difference in the two numbers is proportional to the way the heat transfer coefficient is varying across the plate measurement area as a consequence of the boundary layer growth.

These calculations indicate there apparently is some potential for errors arising to the way the air flows across the plate. It is difficult to tell if this error is important.

One way to look at the possible error arising due to nonuniform heat transfer across the measurement area is to perform material property measurements under different air flow conditions and see if the measured properties vary in some systematic way.

Natick conducted such a series of tests using one of the Saratoga control samples. First a series of bare plate tests were conducted over several air velocities between 0.5 and 2.0 m/s. Then one of the Saratoga control samples was tested under the same conditions. If the air flow causes significant errors, the measured intrinsic thermal resistance of the Saratoga sample would show some change as a function of air velocity.

Figure D-3 shows that no large errors are apparent over the air velocity range used. The measured intrinsic thermal resistance remains constant over the entire range of velocities. The single value for still air, or natural convection, is extrapolated from another series of tests conducted previously[1].

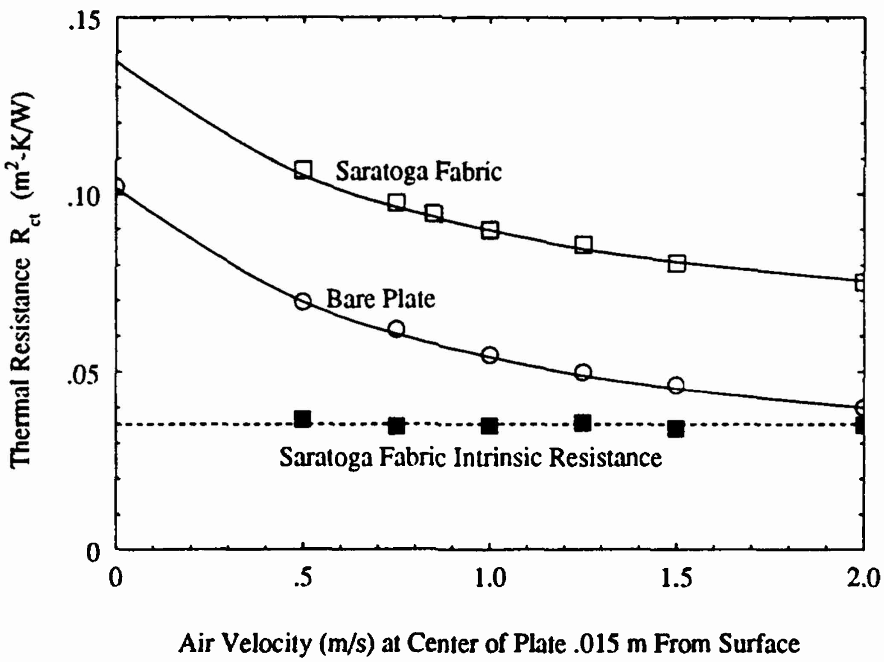

Figure D-3. Variation of Measured Thermal Resistance with Air Velocity Over Plate Surface.

Figure D-3 implies that the errors introduced by the non-uniform boundary layer in the ISO 11092 standard do not significantly affect the measured properties. Figure D-3 also shows that the measured properties do not vary significantly over quite a wide velocity range. For the five different air velocities used, the measured properties of the Saratoga thermal resistance show a coefficient of variation of about 3%, which is as good as the normal test-to-test variability for an identical sample using standard conditions.