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COMPARATIVE STUDY OF HEAT TRANSFER AND WATER VAPOR PERMEABILITY AT THREE LABORATORIES

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Heat transfer and water vapor transport measurements of materials were performed by three laboratories on-site at the U.S. Army Natick Research, Development and Engineering Center and compared. All three laboratories determine the thermal and water vapor transport properties of clothing materials and evaluate them for their intended use. Differences in test procedures and equipment result in different reported properties; this study evaluated which factors are most important. It was found that the air speed over the guarded hot plate is the biggest source of discrepancies in reported material property results. The effect of air speed can be understood by examining the relative proportions of heat lost by convection and evaporation, which increase at higher air speeds, and the heat lost by radiation, which remains constant The thermal and water vapor transport data generated by the three laboratories agree well if the variation in air speed over the plate is taken into account. A small bias between laboratories does exist, but is not significant for most materials. Measured intrinsic properties should agree within 10% for all the laboratories. Better agreement is possible if identical test conditions are used by all three laboratories.

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PREFACE

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

The study was undertaken after Dr. Don Rivin of the Materials Research and Engineering Division of IPD noticed that thermal property data generated by the different laboratories on the same materials did not agree. Because the data were difficult to trace, it was not certain if the reason for the discrepancy was due to confusion over the units reported or if the results were truly different. The Individual Protection Directorate agreed to prepare a set of test samples, distribute them to the three laboratories, and produce a report on the results.

All NCTRF tests were conducted by Joe Giblo of the Environmental Sciences Division. USARIEM tests were conducted by Thomas L. Endrusick of the Biophysics and Biomedical Modeling Division. IPD tests were conducted by Phil Gibson of the Materials Research and Engineering Division.

The author expresses his appreciation to John R. Breckenridge of USARIEM for his careful reading of the draft report and his helpful suggestions, many of which were incorporated into this report.

Comparative Study of Heat Transfer and Water Vapor Permeability at Three Laboratories

1. Introduction

Three organizations on-site 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 Individual Protection Directorate (IPD) 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 determine the thermal and water vapor transport properties of materials and evaluate these materials for their intended use.

Each facility conducts laboratory tests based on the same concepts and principles, but which differ in the actual test conditions. Occasionally the need arises to compare materials tested at one laboratory with materials tested at another facility. Because of the differences in test procedure among the three laboratories, this comparison can be very difficult.

The intent of this study is not to standardize test procedures, although that may come about at some point, but rather to observe how the differences in standard practice at each laboratory influence material property results obtained with these test methods. This report also documents the equipment and procedures currently used by each facility.

2. Materials and Methods

Materials

Each laboratory was asked to determine the thermal and water vapor transport properties of two different materials. Three samples of each material were provided.

The first material was a nylon/cotton blend fabric used in the U.S. Army's Battle Dress Uniform[1]. This material is a 50% nylon, 50% cotton fabric printed with a Woodland camouflage pattern.

The second material was a carbon-impregnated polyurethane foam, which is used as the inner liner of the Battle Dress Overgarment[2] (BDO). It is composed of a nylon tricot knit fabric laminated together with a polyurethane foam, which incorporates activated carbon particles in an acrylic binder for chemical agent adsorption.

Each sample was measured by the Individual Protection Directorate (IPD) for weight, thickness, areal density, and bulk density, before it was given to the laboratory for testing. Each sample was assigned a number for later tracking. A tabulation of measurements for each sample is given in Appendix A.

Methods

Each facility uses a guarded hot plate apparatus to determine dry thermal resistance and water vapor permeability of materials. The general principles of a guarded hot plate apparatus may be found in Reference 3. The guarded hot plate measures the power required to maintain a flat isothermal 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.

A general description of each of the two types of tests follows.

Dry Thermal Resistance

Dry thermal resistance 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:

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

R_{total} = Thermal resistivity of material plus the boundary air layer
A = Surface area of guarded plate measurement area
T_{plate} = Temperature of the plate surface
T_{air} = Temperature of the ambient air
Q = Power required to maintain a constant plate surface temperature

The units used in this report are :

R_{total} given in clo (clo is a unit of thermal resistance and is equal to 0.155 °C-m^2/watt)

A given in m^2

T_{plate} and T_{air} given in °C

Q given in watts

The total thermal resistance R_{total} includes the apparent thermal resistance of the boundary air layer above the fabric material surface. The thermal resistance of this 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_0.

R_0 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. 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_i of the fabric may be obtained by subtracting out the thermal resistance of the overlying boundary air layer:

$$R_i = R_{total} - R_0$$

R_{total} is very sensitive to the effect of air speed, while R_i should be much less sensitive and is more of an intrinsic material property. R_i may also be affected by wind penetration into or through the fabric, particularly for materials with high air permeability. This effect can become very important if the wind direction is perpendicular to the plate, or if there is an air space between the fabric and the plate.

Water Vapor Permeability

Water vapor permeability of materials can be measured with a guarded hot plate by saturating the plate surface with water. The power required to maintain the surface at a given temperature is related to the rate at which water evaporates from the surface of the plate and diffuses through the material. The thermal resistance of the material to convective heat transfer must be known before it is possible to extract the vapor permeability coefficient. Woodcock[4] developed a moisture vapor permeability index, known as i_m, which serves as a very convenient relative measure of the moisture vapor permeability of materials.

$$i_m = \frac{\left\{\frac{(Q)(R_{total})}{A}\right\} - \left(T_{plate} - T_{air}\right)}{S\left(p_s - \phi p_a\right)}$$

i_m = Moisture vapor permeability index
R_{total} = Thermal resistivity of the fabric plus the boundary air layer
A = Surface area of guarded plate measurement area
T_{plate} = Temperature of the saturated plate surface
T_{air} = Temperature of the ambient air
Q = Power required to maintain a constant saturated plate surface temperature
S = Lewis relation between evaporative mass transfer coefficient and convective heat transfer coefficient
p_s = Saturated water vapor pressure at the plate surface
p_a = Saturated water vapor pressure of the ambient air
ϕ = Relative humidity of ambient air

The units used in this report are :

R_{total} given in clo

A given in m^2

T_{plate} and T_{air} given in °C

Q given in watts

S given as 2.2 °C/mmHg

p_a and p_s given in mmHg

ϕ given in fractional relative humidity (not %)

The i_m value is a relative measure of the permeability of the material to the passage of water vapor. The i_m index should vary between 0 (for completely impermeable materials), and 1 (for completely permeable materials). In practice, the value of 1 as an upper limit is not approached until the wind speed over the plate becomes great enough to minimize the contribution of radiative heat transfer, as will be shown later.

The moisture vapor permeability index, i_m, may be combined with the total dry thermal resistance, R_{total}, to yield a quantity which takes into account both convective and evaporative heat transfer. In this report R_{total} is given in clo units, so the term becomes i_m/clo. The term i_m/clo provides a good ranking measure between materials if one is interested in materials which minimize the potential for heat stress. The higher the value for i_m/clo, the easier it is for heat to be dissipated through the materials via both evaporative cooling and convective heat transfer. However, when the ambient humidity is high and wind speed is low, evaporative cooling becomes less important, and the dry thermal resistance (clo) is the most important property.

Both IPD and NCTRF routinely use i_m/clo as a discriminator between materials. USARIEM measures and reports its measured quantities using a different nomenclature and method[5]. USARIEM's values were converted to the same units used by IPD and NCTRF to make comparison of results convenient. Appendix B shows the relationship between the quantities and nomenclature reported by USARIEM and the procedure used to convert values from one form to another.

Individual Laboratory Test Methods

The most important difference between the test methods used by IPD, NCTRF, and USARIEM is the velocity of the air flowing over the guarded hot plate. NCTRF conducts both dry thermal resistance and water vapor permeability testing according to air flow conditions as set forth in ASTM Method D-1518[3]. USARIEM and IPD normally conduct tests where the air flow rate is much higher than called for in the ASTM standard. It should be noted that the ASTM standard only applies to dry thermal testing and that there is no ASTM standard for this type of water vapor permeability testing. USARIEM tests are conducted according to DIN Standard 54-101[6].

To provide a full range of test conditions IPD repeated all the thermal tests under conditions of natural convection, where there was no air flow over the plate. This provided a wide range of air flow velocities.

The general test conditions for each laboratory are shown in Tables 1 and 2. More complete information on the equipment and methods used is contained in Appendix C.

Table 1. Dry Thermal Resistance Test Conditions

Condition	IPD (Still Air)	NCTRF	USARIEM	IPD (Normal)
Air Velocity (m/sec)	0.0	0.1	1.0	2.0
T_{plate} (°C)	35	33	35	35
T_{air} (°C)	22-25	20	20	10
Relative Humidity (%)	50-60	50	65	50

Table 2. Water Vapor Permeability Test Conditions

Condition	IPD (Still Air)	NCTRF	USARIEM	IPD (Normal)
Air Velocity (m/sec)	0.0	0.1	1.0	2.0
T_{plate} (°C)	35	33	35	35
T_{air} (°C)	22-25	26.7	35	32.2
Relative Humidity (%)	50-60	80	40	80

3. Results

All test results are tabulated in Appendix D. 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 D.

Bare Plate Results

Each laboratory tests under different air flow conditions. The influence of air velocity upon test results for the calibration run of the bare guarded hot plate is obvious in Figures 1 and 2.

Figure 1 shows the influence of air velocity upon the measured thermal resistance of the boundary air layer above the guarded hot plate. As the air velocity increases from the stagnant condition, more of the insulating boundary air layer is stripped away, lowering the measured bare plate thermal resistance (R_0).

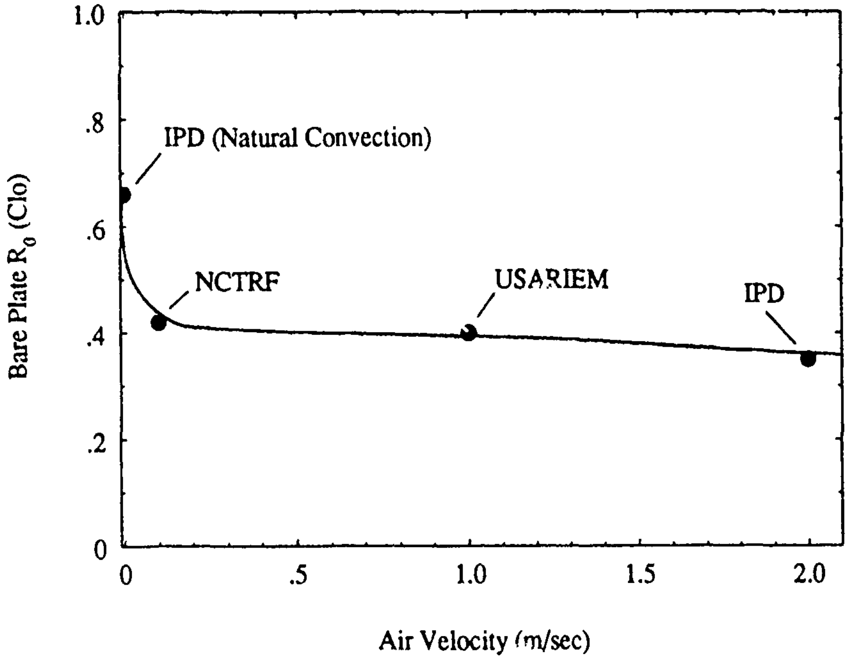

Figure 1
Effect of Air Velocity on Measured Bare Plate Thermal Resistance (R_0)

Changes in air velocity also affect the measured bare plate i_m value. As the air velocity over the plate increases, the evaporation rate from the plate surface also increases, until the i_m value approaches the limiting value of 1.0 for high air flow velocities. The measured value of i_m for the three laboratories is shown in Figure 2.

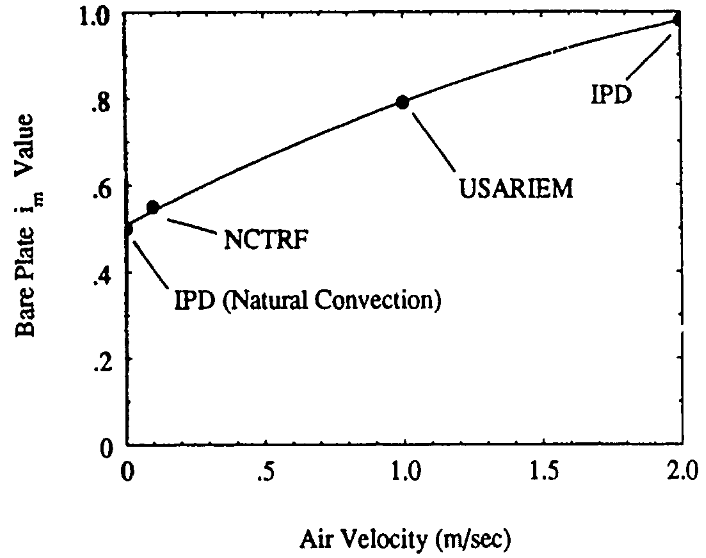

Figure 2
Effect of Air Velocity on Measured Bare Plate Vapor Permeability Index (i_m)

This effect of air velocity on the measured value of i_m is well known, and agrees with data obtained by Woodcock during the original development of the concept of the i_m index. Figure 3 shows bare plate data obtained by Woodcock[4] plotted along with the data from Figure 2. The variation in i_m with wind speed is due to radiative heat transfer, which becomes an appreciable portion of the total heat transfer at very low air speeds, when the thermal and mass transfer resistance of the boundary air layer greatly increases. The variation in i_m with wind speed is not due to changes in the Lewis relation S, although Spencer-Spivey[6] proposed that S does show a slight dependence on both wind speed and the geometry of the heated isothermal surface. A short discussion of the importance of air flow over the plate is given in Appendix E.

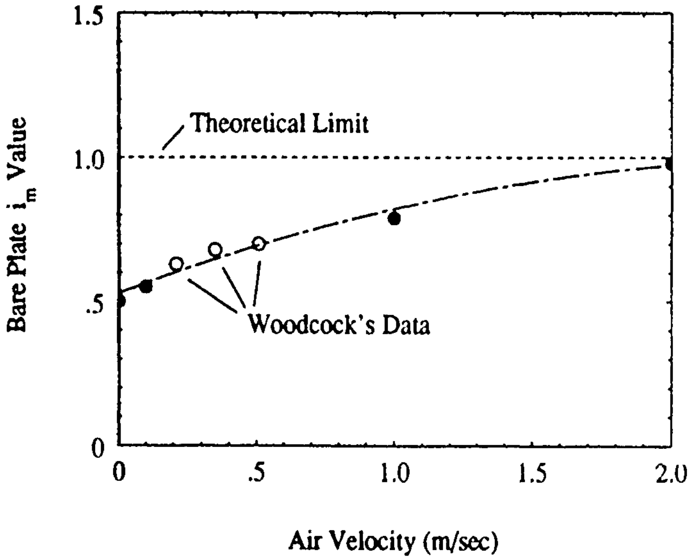

Figure 3
Effect of Air Velocity on Measured Bare Plate Vapor Permeability Index (i_m), Including Woodcock's Data

In addition to the differences in air flow velocity over the guarded hot plate, each laboratory also tests at different plate temperatures and ambient humidities. These variables have little effect on measured i_m values. Giblo[8] showed that the measured bare plate i_m value does not change appreciably over a wide range of temperature and humidity conditions as long as the air flow conditions remain the same. Unpublished data from IPD for a narrower range of conditions also show no change in bare plate i_m values as the plate temperature, air temperature, and the air relative humidity are varied.

Fabric Results

The results for the two types of materials, the BDU fabric and the CP foam material, are shown in Figures 4 and 5. These two figures show that all the measurements which include the properties of the boundary air layer are highly influenced by the different air flow conditions used by NCTRF, ARIEM, and IPD. Figures 4 and 5 illustrate the difficulty encountered when comparing test results generated by the different laboratories unless the air flow velocity is reported along with the data and taken into account.

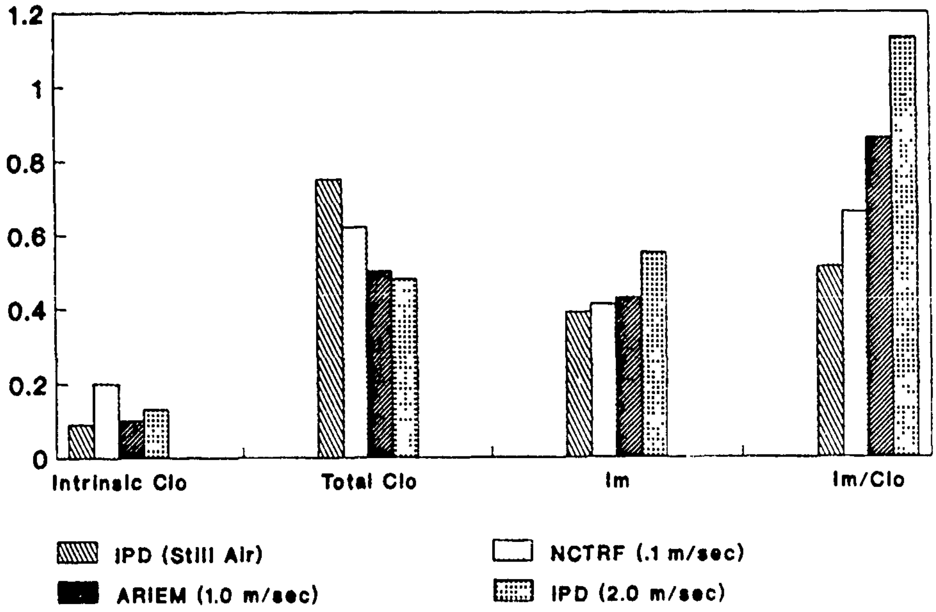

Figure 4
Thermal and Moisture Vapor Permeability Results for the Battle Dress Uniform (BDU) Fabric

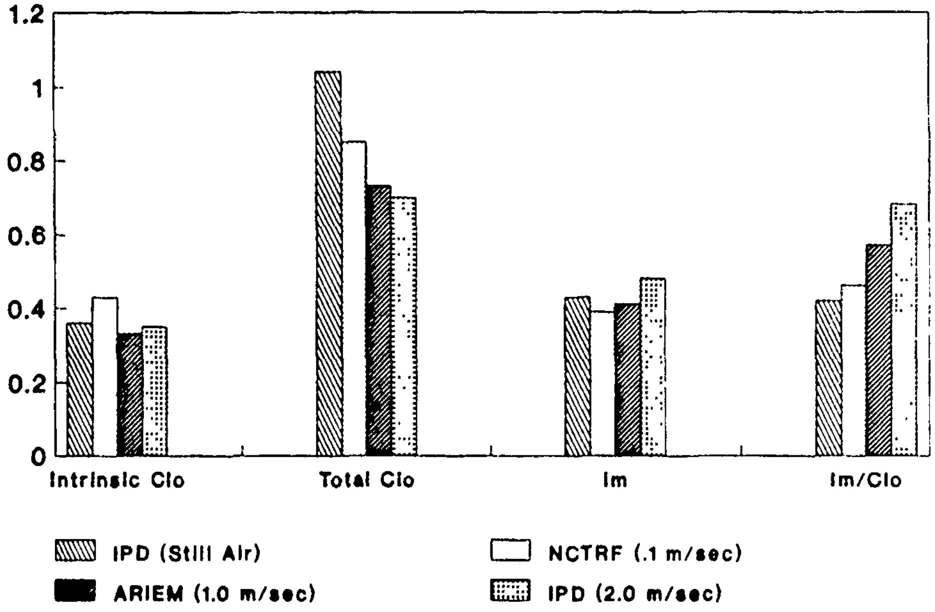

Figure 5
Thermal and Moisture Vapor Permeability Results for the Chemical Protective (CP) Foam

The only measurements theoretically unaffected by the air flow velocity are the intrinsic clo values. It's clear from Figures 4 and 5 that there is no systematic relationship of intrinsic clo value to air speed as there is for the other quantities. The actual variability in intrinsic material properties among the three laboratories will be discussed later in this report.

Effect of Air Velocity on Measured Properties

The influence of air flow velocity over the guarded hot plate upon measured properties becomes much clearer if the data from each lab are plotted as a function of air flow. Figures 6 and 7 show the i_m and i_m/clo values obtained for the two materials as a function of air velocity over the guarded hot plate.

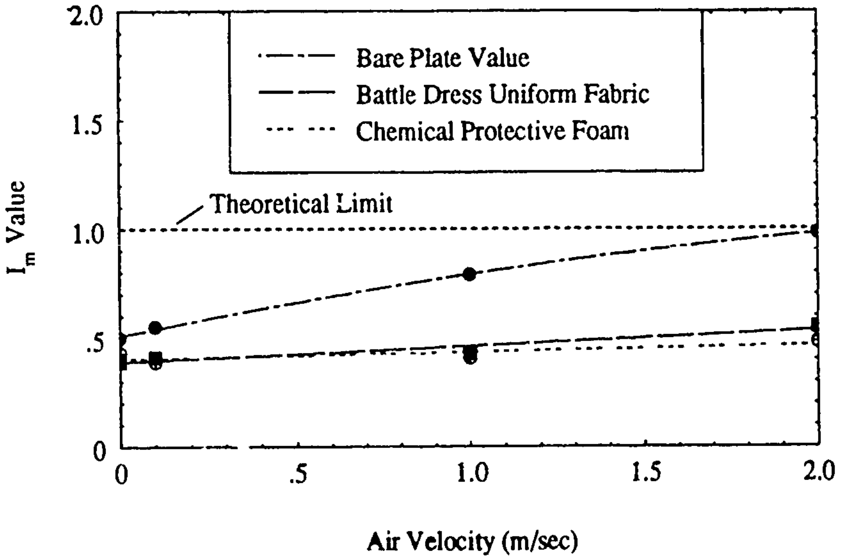

Figure 6
Water Vapor Permeability Index (i_m) of the Battle Dress Uniform Fabric and the Chemical Protective Foam Determined Under Several Air Flow Conditions.

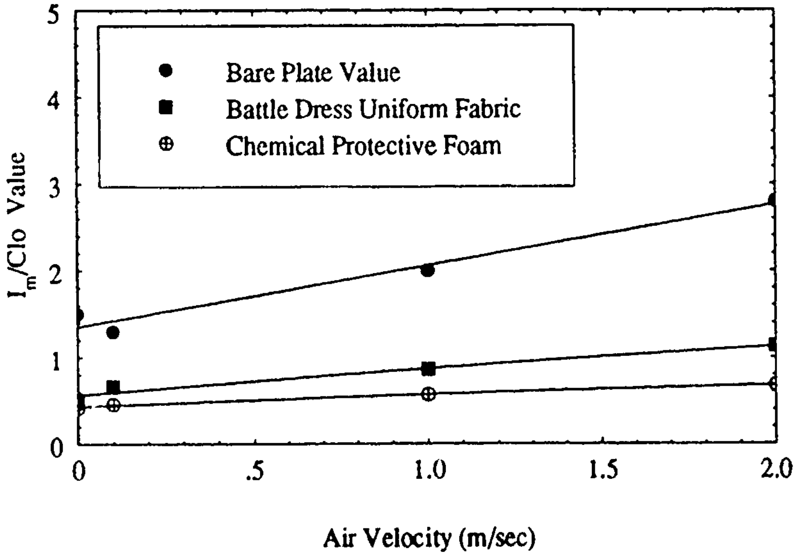

Figure 7
I_m/Clo Values of the Battle Dress Uniform Fabric and the Chemical Protective Foam Determined Under Several Air Flow Conditions

The two materials follow the same trends as the bare plate results. The normal test procedures for all three laboratories show that the BDU fabric has better water vapor transmission characteristics (i_m) and more potential for heat stress reduction (i_m/clo) than the CP foam. For the still air condition only, the relative i_m ranking between the two materials is reversed, although it is also clear from Figure 6 that the still air i_m values for these two materials are essentially identical. It is also interesting to note that the relative differences between materials are much more pronounced at the higher air flow velocities. This makes distinguishing differences between materials much easier, which is, after all, the reason for performing guarded hot plate tests in the first place.

The slope of the regression-fit line for each material differs. This variation is in line with previous experience obtained with thermal heated mannikins, which shows that thermal properties of different clothing ensembles are proportional to different powers of the air velocity[9].

Unfortunately, the different slope of the regression lines for each material means that it is not possible to normalize data from the three laboratories based on a simple correction factor. It is encouraging that even though the BDU fabric and the CP foam material are very different in composition and structure, they seem to follow the same trend. One should be able to "eyeball" the proper slope for a different material and be able to determine the properties which would be measured at each laboratory, given the results generated at another laboratory.

Variability of Intrinsic Fabric Properties

The measurements of i_m and i_m/clo include the boundary air layer above the plate. This makes direct comparison of the values reported by IPD, USARIEM, and NCTRF difficult. It is easier to compare the true variability of results by subtracting out the influence of the air layer and comparing the intrinsic properties of the materials. Appendix B defines three intrinsic material properties used by USARIEM: R_{ct}, R_{et}, and i_{mt}. These intrinsic properties were also calculated for the NCTRF and IPD data and are listed in the tables in Appendix D.

The intrinsic insulation value R_{ct} is identical to the intrinsic clo value for all the materials, except that it is given in units of m^2-K/watt. R_{et} is the equivalent water vapor resistance (essentially a resistance to mass transfer rather than heat transfer), given in units of m^2-mbar/watt.

Figures 8 and 9 show the calculated values for R_{ct} and R_{et} plotted along with the sample coefficient of variance (error bars) for each laboratory. The error bars were calculated based on the three samples of each material supplied to each laboratory. A reference line which shows the average value calculated using the data from all four test conditions is also shown on these figures. Each laboratory has a comparable sample-to-sample variability. The repeatibility of measurement is excellent for the normal test procedures of the three laboratories.

There is a definite bias in the intrinsic properties reported by each laboratory. Both Figure 8 and 9 show a similar pattern of interlaboratory variation. The differences are not very large, but they are real

For all test conditions, the coefficient of variance of all four average value of R_{ct} and R_{et} is approximately 10%, except for the intrinsic thermal resistance R_{ct} of the Battle Dress Uniform fabric, where the interlaboratory coefficient of variation is approximately 30%.

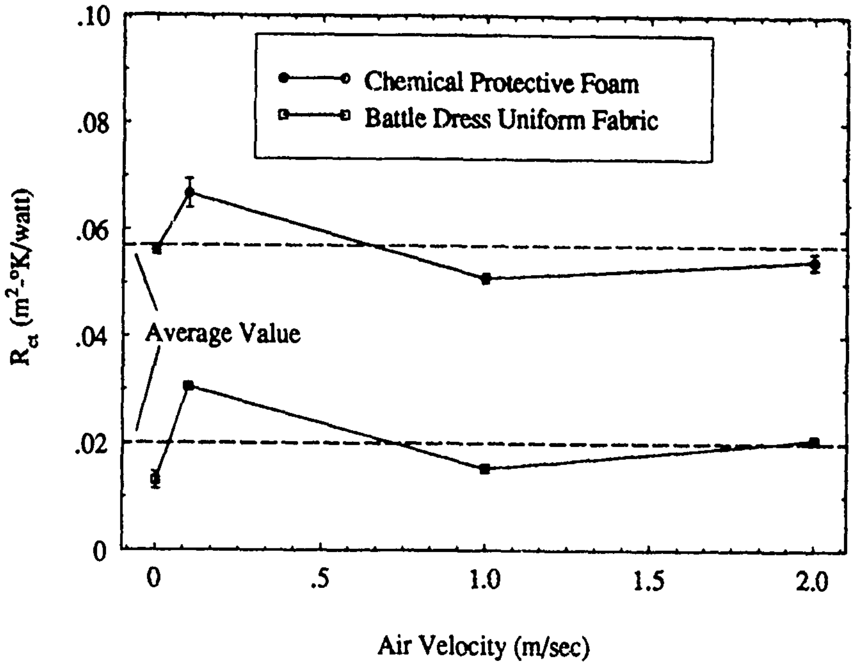

Figure 8
Interlaboratory Variation in Intrinsic Thermal Resistance R_{ct} for the Battle Dress Uniform Fabric and the Chemical Protective Foam

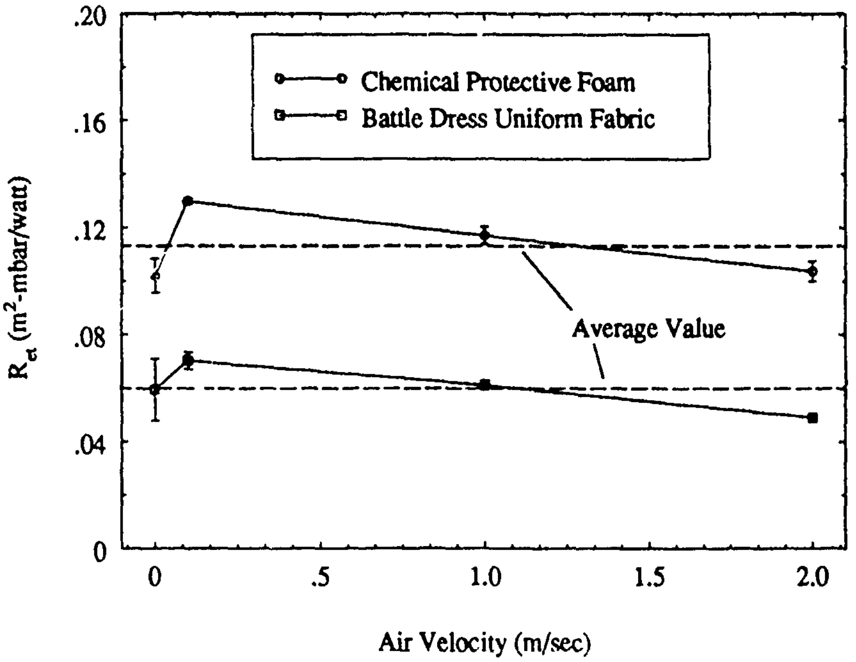

Figure 9
Interlaboratory Variation in Intrinsic Water Vapor Resistance R_{et} for the Battle Dress Uniform Fabric and the Chemical Protective Foam Material

4. Conclusions and Recommendations

Conclusions

- Guarded hot plate thermal and water vapor transport data generated by IPD, USARIEM, and NCTRF agree well if the variation in air speed over the plate is taken into account.

- A small bias between facilities does exist. NCTRF consistently measured a higher intrinsic thermal resistance, while IPD measured the lowest value of intrinsic thermal resistance. NCTRF also reported the highest values of water vapor resistance, while USARIEM measured the lowest values. The bias is not significant for most materials. Measured intrinsic thermal and mass transfer properties should agree within 10% for all the laboratories. Better agreement is probably possible only if identical test conditions are used.

Recommendations

- Determine the absolute bias of each laboratory's guarded hot plate apparatus with a calibrated fiberglass sample of known thermal conductivity obtained from the National Institute of Standards and Technology (NIST).

- Laboratories must always report test conditions, especially air speed over the plate, along with thermal property and water vapor transport data. NCTRF does this implicitly by adhering to the ASTM Standard D1518[3], which contains air velocity limits, but in the past IPD frequently sent fabric test results out with no reference to the test conditions used.

- Test conditions which produce a bare plate i_m value approaching the limit of 1.0 make it easier to distinguish differences between similar materials. Air velocities of at least 1.0 meter/second, and preferably higher, should be used during moisture vapor permeability testing.

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in the series of reports approved for publication

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APPENDIX A

Physical Properties of Fabric Samples

Table A-1. Physical Property Data for IPD Samples

Sample I.D.	Thickness (in)	Weight (g)	Area (in^2)	Areal Density (oz/yd^2)	Bulk Density (lb/ft^3)
cp-1	0.121	99.0	484.0	9.3	6.4
cp-5	0.120	100.2	484.0	9.5	6.6
cp-7	0.128	101.0	484.0	9.5	6.2
Average	0.123	100.07	484.00	9.43	6.40
Variance (biased)	0.000	0.68	0.00	0.01	0.03
% Variance (biased)	2.89	0.82	0.00	1.00	2.55
Std. Deviation (biased)	0.00	0.82	0.00	0.09	0.16
Variance (unbiased)	0.000	1.01	0.00	0.01	0.04
% Variance (unbiased)	3.54	1.01	0.00	1.22	3.13
Std. Deviation (unbiased)	0.004	1.007	0.000	0.115	0.200
bdu-1	0.04	85.00	484.00	8.00	15.60
bdu-5	0.04	85.60	484.00	8.10	15.70
bdu-7	0.04	82.60	484.00	7.80	15.10
Average	0.043	84.40	484.00	7.97	15.47
Variance (biased)	0.000	1.68	0.00	0.02	0.07
% Variance (biased)	0.00	1.54	0.00	1.57	1.70
Std. Deviation (biased)	0.00	1.30	0.00	0.12	0.26
Variance (unbiased)	0.000	2.52	0.00	0.02	0.10
% Variance (unbiased)	0.000	1.88	0.00	1.92	2.08
Std. Deviation (unbiased)	0.000	1.587	0.000	0.153	0.321

Table A-2. Physical Property Data for NCTRF Samples

Sample I.D.	Thickness (in)	Weight (g)	Area (in^2)	Areal Density (oz/yd^2)	Bulk Density (lb/ft^3)
cp-3	0.125	97.9	484.0	9.3	6.2
cp-8	0.129	103.4	484.0	9.8	6.3
cp-9	0.125	102.7	484.0	9.7	6.5
Average	0.126	101.33	484.00	9.57	6.31
Variance (biased)	0.000	5.98	0.00	0.05	0.02
% Variance (biased)	1.49	2.41	0.00	2.39	1.95
Std. Deviation (biased)	0.00	2.44	0.00	0.23	0.12
Variance (unbiased)	0.000	8.96	0.00	0.08	0.02
% Variance (unbiased)	1.83	2.95	0.00	2.93	2.39
Std. Deviation (unbiased)	0.002	2.994	0.000	0.280	0.151
bdu-3	0.04	84.80	484.00	8.01	16.28
bdu-8	0.04	86.80	484.00	8.20	16.27
bdu-9	0.04	87.00	484.00	8.22	17.12
Average	0.041	86.20	484.00	8.14	16.56
Variance (biased)	0.000	0.99	0.00	0.01	0.16
% Variance (biased)	1.99	1.15	0.00	1.15	2.40
Std. Deviation (biased)	0.00	0.99	0.00	0.09	0.40
Variance (unbiased)	0.000	1.48	0.00	0.01	0.24
% Variance (unbiased)	2.44	1.41	0.00	1.41	2.94
Std. Deviation (unbiased)	0.000	1.217	0.000	0.115	0.487

Table A-3. Physical Property Data for USARIEM Samples

Sample I.D.	Thickness (in)	Weight (g)	Area (in^2)	Areal Density (oz/yd^2)	Bulk Density (lb/ft^3)
cp-2	0.119	99.9	484.0	9.4	6.6
cp-4	0.121	99.9	484.0	9.4	6.5
cp-6	0.120	100.5	484.0	9.5	6.6
Average	0.120	100.1	484.00	9.45	6.57
Variance (biased)	0.000	0.08	0.00	0.001	0.02
% Variance (biased)	0.68	0.28	0.00	0.28	0.73
Std. Deviation (biased)	0.008	0.28	0.00	0.03	0.048
Variance (unbiased)	0.000	0.120	0.00	0.001	0.004
% Variance (unbiased)	0.83	0.35	0.00	0.34	0.90
Std. Deviation (unbiased)	0.001	0.346	0.000	0.032	0..059
bdu-2	0.04	85.80	484.00	8.10	15.35
bdu-4	0.05	85.80	484.00	8.10	14.68
bdu-6	0.05	85.50	484.00	8.08	14.02
Average	0.046	85.70	484.00	8.09	14.68
Variance (biased)	0.000	0.02	0.00	0.0002	0.29
% Variance (biased)	3.55	0.17	0.00	0.16	3.70
Std. Deviation (biased)	0.002	0.14	0.00	0.013	0.54
Variance (unbiased)	0.000	0.03	0.00	0.0003	0.44
% Variance (unbiased)	4.35	0.20	0.00	0.20	4.53
Std. Deviation (unbiased)	0.002	0.173	0.000	0.016	0.665

APPENDIX B

Conversion Factors for USARIEM Data

USARIEM reports most of its thermal and water vapor permeability data based on the intrinsic properties of the material, after subtracting out the properties of the boundary air layer. USARIEM also measures its water vapor permeability without a temperature gradient between the plate and the ambient atmosphere. USARIEM follows the DIN Standard 54-101, which specifies that temperature be reported in K rather than °C, where K = °C + 273.

USARIEM reported data values for R_{ct}, R_{et}, and i_{mt}, which are defined below:

Thermal resistance, $$R_{ct} = \frac{(T_{plate} - T_{air})(A)}{Q} - R_{cto}$$

R_{cto} = Bare plate thermal resistance of boundary air layer (m^2-°K/watt)
A = Surface area of guarded plate measurement area (m^2)
T_{plate} = Temperature of the plate surface (°K)
T_{air} = Temperature of the ambient air (°K)
Q = Power required to maintain a constant plate surface temperature (watts)

Water vapor resistance, $$R_{et} = \frac{(p_s - \phi p_a)(A)}{Q} - R_{eto}$$

R_{eto} = Bare plate water vapor resistance of boundary air layer (m^2-mbar/watt)
A = Surface area of guarded plate measurement area (m^2)
T_{plate} = Temperature of the plate surface (°K)
T_{air} = Temperature of the ambient air (°K)
Q = Power required to maintain constant plate surface temperature (watts)
p_s = Saturated water vapor pressure at the plate surface (mbar)
p_a = Saturated water vapor pressure of the ambient air (mbar)
ϕ = Relative humidity (fractional)

Intrinsic water vapor permeability index i_{mt} is given by:

$$i_{mt} = S_l\left(\frac{R_{ct}}{R_{et}}\right)$$

where S_l is 0.6 mbar/°K (or 0.45 mmHg/°C), and is equal to 1/S (S defined previously as 2.2 °C/mmHg).

The conversion factor used to convert USARIEM data to the units used in the body of the report is shown below:

Bare plate thermal resistance $R_0 = (6.46)R_{cto}$
Total thermal resistance $R_{total} = (6.46)(R_{cto}+R_{ct})$
Intrinsic thermal resistance $R_i = (6.46)R_{ct}$

where R_0, R_{total}, and R_i are in clo units; R_{cto} and R_{ct} are in m^2-K/watt.

The water vapor permeability index i_m is found from:

$$i_m = S_1 \left\{ \frac{(R_{ct} + R_{cto})}{(R_{et} + R_{eto})} \right\}$$

The IPD and NCTRF data were also converted to the USARIEM system of units to obtain the intrinsic material values of R_{ct}, R_{et}, and i_{mt}, using the relations outlined above.

APPENDIX C

Test Equipment

Individual Protection Directorate (IPD)

Plate Manufacturer: Dynatech R/D Company (reorganized as Holometrics, 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

Chamber Air Speed: approximately 2 m/sec

Air Speed Control: None. Air speed determined by forced air circulation of fan.

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

Plate Manufacturer: Dynatech R/D Company (reorganized as Holometrics, Inc.)

Plate Dimensions: Measurement Area = 0.0645 m^2
Guard Area = 0.1935 m^2

Chamber Manufacturer: Envirotronics

Chamber Volume: 0.84 m^3

Chamber Air Speed: approximately 2.5 m/sec

Air Speed Control: Air speed controlled to approximately 0.1 m/sec by means of a plexiglass box containing horizontal slits, which sits over the plate.

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 (guard area is not saturated
during a vapor permeability test)

Chamber Manufacturer: Weiss Umwelttechnik, GMBH (Federal Republic of Germany)

Chamber Volume: 0.64 m^3

Chamber Air Speed: N/A

Air Speed Control: Excellent air speed control made possible by a hood and manifold, which produce a laminar air flow over the plate. Air speed is adjustable +/- 5% .

APPENDIX D

Thermal Property Data

Table D-1. Individual Protection Directorate (IPD) Thermal Property Data

Air speed = 2 m/sec
Bare plate clo = 0.35
Bare plate i_m = 0.98

Sample I.D.	Intrinsic Clo (R_i)	Total Clo (R_{total})	I_m	I_m/Clo (I_m/R_{total})	R_{ct} (m^2-K/watt)	R_{et} (m^2-mbar/watt)	I_{mt} (R_{ct}/R_{et})
cp-1	0.35	0.70	0.47	0.67	0.0542	0.1052	0.31
cp-5	0.33	0.68	0.44	0.64	0.0511	0.1104	0.28
cp-7	0.37	0.72	0.52	0.72	0.0573	0.0954	0.36
Average	0.35	0.70	0.48	0.68	0.05	0.10	0.32
Variance (biased)	0.00	0.00	0.00	0.00	0.00	0.00	0.00
% Variance (biased)	4.67	2.33	6.92	4.88	4.67	5.97	10.76
Std. Deviation (biased)	0.02	0.02	0.03	0.03	0.00	0.01	0.03
Variance (unbiased)	0.00	0.00	0.00	0.00	0.00	0.00	0.00
% Variance (unbiased)	5.71	2.86	8.48	5.97	5.71	7.32	13.17
Std. Deviation (unbiased)	0.020	0.020	0.040	0.040	0.003	0.008	0.042
bdu-1	0.14	0.49	0.56	1.13	0.0217	0.0481	0.27
bdu-5	0.13	0.48	0.53	1.10	0.0201	0.0509	0.24
bdu-7	0.13	0.48	0.55	1.15	0.0201	0.0479	0.25
Average	0.13	0.48	0.55	1.13	0.02	0.05	0.25
Variance (biased)	0.00	0.00	0.00	0.00	0.00	0.00	0.00
% Variance (biased)	3.54	0.98	2.28	1.82	3.54	2.85	5.38
Std. Deviation (biased)	0.00	0.00	0.01	0.02	0.00	0.00	0.01
Variance (unbiased)	0.00	0.00	0.00	0.00	0.00	0.00	0.00
% Variance (unbiased)	4.33	1.19	2.79	2.23	4.33	3.49	6.59
Std. Deviation (unbiased)	0.006	0.006	0.015	0.025	0.001	0.002	0.017

Table D-2. Individual Protection Directorate (IPD) Thermal Property Data Still Air Conditions (Natural Convection)

Air speed = 0.0 m/sec
Bare plate clo = 0.66
Bare plate $i_m = 0.50$

Sample I.D.	Intrinsic Clo (R_i)	Total Clo (R_{total})	I_m	I_m/Clo (I_m/R_{total})	R_{ct} (m^2-K/watt)	R_{et} (m^2-mbar/watt)	I_{mt} (R_{ct}/R_{et})
cp-1	0.37	1.03	0.45	0.44	0.0573	0.0902	0.38
cp-5	0.37	1.03	0.43	0.42	0.0573	0.1001	0.34
cp-7	0.35	1.05	0.41	0.40	0.0542	0.1155	0.28
Average	0.36	1.04	0.43	0.42	0.06	0.10	0.34
Variance (biased)	0.00	0.00	0.00	0.00	0.00	0.00	0.00
% Variance (biased)	2.59	0.91	3.80	3.89	2.59	10.20	12.23
Std. Deviation (biased)	0.01	0.01	0.02	0.02	0.00	0.01	0.04
Variance (unbiased)	0.00	0.00	0.00	0.00	0.00	0.00	0.00
% Variance (unbiased)	3.18	1.11	4.65	4.76	3.18	12.50	14.98
Std. Deviation (unbiased)	0.012	0.012	0.020	0.020	0.002	0.013	0.050
bdu-1	0.07	0.73	0.33	0.45	0.0108	0.0831	0.08
bdu-5	0.08	0.74	0.38	0.51	0.0124	0.0585	0.13
bdu-7	0.11	0.77	0.45	0.58	0.0170	0.0365	0.28
Average	0.09	0.75	0.39	0.51	0.01	0.06	0.16
Variance (biased)	0.00	0.00	0.00	0.00	0.00	0.00	0.01
% Variance (biased)	19.61	2.28	12.73	10.35	19.61	32.02	53.06
Std. Deviation (biased)	0.02	0.02	0.05	0.05	0.00	0.02	0.09
Variance (unbiased)	0.00	0.00	0.00	0.00	0.00	0.00	0.01
% Variance (unbiased)	24.02	2.79	15.59	12.67	24.02	39.22	64.99
Std. Deviation (unbiased)	0.021	0.021	0.060	0.065	0.003	0.023	0.105

Table D-3. U.S. Navy Clothing and Textile Research Facility (NCTRF) Thermal Property Data

Air speed = 0.1 m/sec
Bare plate clo = 0.42
Bare plate i_m = 0.55

Sample I.D.	Intrinsic Clo (R_i)	Total Clo (R_{total}]	I_m	I_m/Clo (I_m/R_{total})	R_{ct} (m²-K/watt)	R_{et} (m²-mbar/watt)	I_{mt} (R_{ct}/R_{et})
cp-3	0.45	0.87	0.40	0.46	0.0697	0.1311	0.32
cp-8	0.45	0.87	0.40	0.46	0.0697	0.1311	0.32
cp-9	0.39	0.81	0.38	0.47	0.0604	0.1271	0.29
Average	0.43	0.85	0.39	0.46	0.07	0.13	0.31
Variance (biased)	0.00	0.00	0.00	0.00	0.00	0.00	0.00
% Variance (biased)	6.58	3.33	2.40	1.02	6.58	1.47	5.17
Std. Deviation (biased)	0.03	0.03	0.01	0.00	0.00	0.00	0.02
Variance (unbiased)	0.00	0.00	0.00	0.00	0.00	0.00	0.00
% Variance (unbiased)	8.06	4.08	2.94	1.25	8.06	1.79	6.33
Std. Deviation (unbiased)	0.035	0.035	0.012	0.006	0.005	0.002	0.019
bdu-3	0.20	0.62	0.40	0.65	0.0310	0.0731	0.25
bdu-8	0.20	0.62	0.43	0.69	0.0310	0.0630	0.29
bdu-9	0.19	0.61	0.39	0.64	0.0294	0.0744	0.24
Average	0.20	0.62	0.41	0.66	0.03	0.07	0.26
Variance (biased)	0.00	0.00	0.00	0.00	0.00	0.00	0.00
% Variance (biased)	2.40	0.76	4.18	3.27	2.40	7.23	9.20
Std. Deviation (biased)	0.00	0.00	0.02	0.02	0.00	0.01	0.02
Variance (unbiased)	0.00	0.00	0.00	0.00	0.00	0.00	0.00
% Variance (unbiased)	2.94	0.94	5.12	4.01	2.94	8.85	11.27
Std. Deviation (unbiased)	0.006	0.006	0.021	0.026	0.001	0.006	0.030

Table D-4. U.S. Army Research Institute of Environmental Medicine (USARIEM) Thermal Property Data

Air speed = 1.0 m/sec
Bare plate clo = 0.40
Bare plate i_m = 0.79

Sample I.D.	Intrinsic Clo (R_i)	Total Clo (R_{total})	I_m	I_m/Clo (I_m/R_{total})	R_{ct} (m^2-K/watt)	R_{et} (m^2-mbar/watt)	I_{mt} (R_{ct}/R_{et})
cp-2	0.33	0.73	0.43	0.59	0.0504	0.1106	0.28
cp-4	0.34	0.74	0.40	0.54	0.0530	0.1238	0.26
cp-6	0.32	0.72	0.41	0.57	0.0494	0.1166	0.25
Average	0.33	0.73	0.41	0.57	0.05	0.12	0.26
Variance (biased)	0.00	0.00	0.00	0.00	0.00	0.00	0.00
% Variance (biased)	2.96	1.34	3.02	3.90	2.99	4.60	4.74
Std. Deviation (biased)	0.01	0.01	0.01	0.02	0.00	0.01	0.01
Variance (unbiased)	0.00	0.00	0.00	0.00	0.00	0.00	0.00
% Variance (unbiased)	3.63	1.64	3.70	4.78	3.66	5.64	5.80
Std. Deviation (unbiased)	0.012	0.012	0.015	0.027	0.002	0.007	0.015
bdu-2	0.10	0.50	0.43	0.86	0.0158	0.0602	0.16
bdu-4	0.09	0.49	0.41	0.84	0.0139	0.0648	0.13
bdu-6	0.10	0.50	0.44	0.88	0.0158	0.0584	0.16
Average	0.10	0.50	0.43	0.86	0.02	0.06	0.15
Variance (biased)	0.00	0.00	0.00	0.00	0.00	0.00	0.00
% Variance (biased)	5.77	1.14	2.92	1.89	5.78	4.40	9.43
Std. Deviation (biased)	0.01	0.01	0.01	0.02	0.00	0.00	0.01
Variance (unbiased)	0.00	0.00	0.00	0.00	0.00	0.00	0.00
% Variance (unbiased)	7.07	1.39	3.58	2.32	7.07	5.39	11.55
Std. Deviation (unbiased)	0.007	0.007	0.015	0.020	0.001	0.003	0.017

APPENDIX E

Influence of Air Speed on Hot Plate Measurements

The equation for i_m, as developed by Woodcock, incorporates the Lewis relation S, which is the relation between the coefficients of convective heat transfer and evaporative heat transfer. This relation is very useful since for air and water the Lewis relation remains essentially constant as long as atmospheric pressure remains the same.

The validity of the Lewis relation is based on the Chilton-Colburne analogy between heat transfer and mass transfer[10]. Because both convective heat transfer and evaporative heat transfer develop similar gradient profiles, one can infer diffusion parameters from measured convective coefficients[11]. Since it is often easier to measure heat transfer coefficients than diffusion coefficients, this approach is commonly used to obtain diffusion properties. Furthermore, it has been found that if the Lewis number (Le) is close to 1.0, then the convective behavior and diffusive behavior are essentially identical for a wide range of conditions[12].

Note that the Lewis *number* (Le) is not the same as the Lewis *relation* (S). The Lewis number is a dimensionless group similar to the Reynolds number or Prandtl number. The Lewis number relates the thermal diffusivity α to the diffusion coefficient D:

$$Le = \frac{\alpha}{D}$$

For air at 35°C, the thermal diffusivity[13] $\alpha \approx .22$ cm^2/sec, and the diffusion coefficient of water vapor in air[14] $D \approx .26$ cm^2/sec. Thus $Le \approx 1$, and the temperature and water vapor concentration profiles are identical.

The actual value of the Lewis relation S has been shown analytically[15] and experimentally[16] to be about 2.2 °C/mmHg. An example calculation of the Lewis relation S is shown below.

The Lewis relation S is the ratio of the convective heat transfer coefficient h_c and the mass transfer coefficient h_m. The Lewis relation S can also be shown to be defined by[17]:

$$S = \frac{h_c}{h_m} = \rho c_p \left(\frac{Sc}{Pr} \right)^{2/3}$$

ρ = density of air
c_p = heat capacity of air
Sc = Schmidt number of water vapor diffusing in air
Pr = Prandtl number of air

For an air temperature of 65 °F, Sc is 0.6, Pr is 0.7, ρ is 0.0756 lb/ft^3, and c_p is 0.24 Btu/lb-°F; this yields a value of approximately 12.6 psi/°F (or 2.2 °C/mmHg) for the Lewis relation S.

The same relations that apply to the ratio between convective and evaporative heat transfer from the flat saturated guarded hot plate also apply to a wet-bulb thermometer. Experimentally it is known that the temperature depression of a wet-bulb thermometer is constant over a wide range of air velocities once a certain critical air velocity is reached. Normally, the air speed over the wet bulb is recommended to be not less than 3.5 to 4 meters/second[18]. Below this critical air velocity the bulb configuration and air velocity begin to affect the reading[19]. The reason for the inaccuracy of wet-bulb thermometers at the low air velocities is that the Lewis relation neglects radiative heat transfer. At very low air velocities, or under natural convection conditions, the proportion of heat lost by radiation is a significant fraction of the total heat loss or gain.

When there is no air movement over the guarded hot plate, both heat and mass transfer proceed by natural convection. As the air flow rate across the plate increases, the boundary layers over the plate become thinner, and the temperature and concentration gradients through the layers increase. Finally a point is reached where the heat loss due to radiation can be neglected since it is so small in comparison to the convective and evaporative losses. This behavior is apparent in the bare plate results obtained by each laboratory, and is illustrated in Figure E-1. The i_m value steadily rises from a value of 0.5 under natural convection conditions, until i_m approaches its theoretical value of 1.0 at 2 meters/second air velocity.

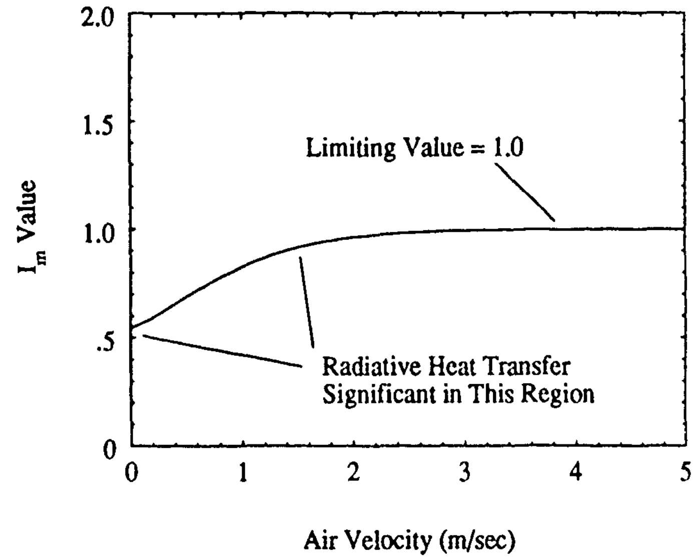

Figure E-1
Bare Plate i_m as a Function of Air Velocity

It should also be clear that the i_m value for the bare plate can only approach 1.0, since there will always be a radiative component of heat loss from the plate.

Figure E-1 also provides justification for performing water vapor permeability testing with a significant air velocity across the plate. The purpose of the guarded hot plate testing is to rank materials with respect to their intrinsic thermal properties. Tests which are performed under natural convection conditions, or at very low air speeds, are mostly measuring the properties of the boundary air layer over the plate. The fabric properties are usually a small portion of the total resistance to heat and vapor transfer at low air speeds. Testing at higher air speeds can also help distinguish between similar materials, since the range of the measurement is expanded. An example of this is given in the body of the report in Figure 7. It is much easier to distinguish the difference between the BDO Fabric and the CP Foam when the air speed over the plate is 2.0 m/sec, than when the materials were tested under still air conditions.

In addition, at low air speeds, the radiative heat loss becomes more important. Differences in the emissivity of two fabrics may lead to a large difference in total heat transfer due not to higher permeability, but due to the fact that one fabric may simply be of a different color (different emissivity). Testing at high air velocities minimizes the contribution of radiant heat loss to the guarded hot plate measurement.