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TECHNICAL REPORT
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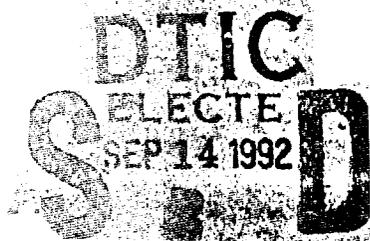
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Comparison of Sweating Guarded Hot Plate and Upright Cup Methods of Measuring Water Vapor Permeability

Phillip W. Gibson

August 1992

Final Report
June 1991 - September 1991

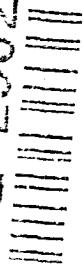


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1. AGENCY USE ONLY (Leave blank)		2. REPORT DATE August 1992	3. REPORT TYPE AND DATES COVERED Final June 1991/September 1991	
4. TITLE AND SUBTITLE Comparison of Sweating Guarded Hot Plate and Upright Cup Methods of Measuring Water Vapor Permeability			5. FUNDING NUMBERS Proj. I.D. : 62723 AH98	
6. AUTHOR(S) Gibson, Phillip				
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) U.S. Army Natick RD&E Center Kansas Street, ATTN: SATNC-ITFR Natick, MA 01760-5019			8. PERFORMING ORGANIZATION REPORT NUMBER NATICK/TR-92/046	
9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)			10. SPONSORING / MONITORING AGENCY REPORT NUMBER	
11. SUPPLEMENTARY NOTES				
12a. DISTRIBUTION / AVAILABILITY STATEMENT Approved for public release: distribution is unlimited.			12b. DISTRIBUTION CODE	
13. ABSTRACT (Maximum 200 words) Military uniform materials vary widely in their heat transfer and water vapor transport characteristics. In hot environments the water vapor permeability of clothing should be high to maximize evaporative cooling. High water vapor permeability is also important in cold environments to prevent or minimize water buildup in clothing. Several techniques exist to evaluate the water vapor transport characteristics of clothing materials. The most common techniques include guarded hot plate sweating skin simulants and cup-type moisture vapor transmission rate (MVTR) tests. Theoretically all such tests measure an identical property, water vapor resistance, but the results between different types of tests rarely agree. The reasons for the discrepancies are due to the the different conditions present in each test; in some cases the intrinsic properties of the materials are altered by the test conditions. MVTR and sweating skin simulant water vapor resistances correlate quite well for permeable woven and nonwoven textile materials. Semipermeable membranes divide neatly into two types of behavior. Hydrophobic membranes show good correlation between MVTR and sweating skin simulant tests, but hydrophilic membranes show poor agreement between the two types of tests. The scatter is accounted for by noting the different vapor pressure gradient present in the two types of tests, which, when combined with the different levels of water present in the hydrophilic membranes, drastically alters the intrinsic transport characteristics of these hydrophilic membranes. The implications for materials screening testing are discussed.				
14. SUBJECT TERMS Heat Transfer Heat Stress (Physiology) Mass Transfer		Water Vapor Permeable Materials Evaporative Cooling Vapor Permeation Guarded Hot Plate	Thermal Insulation Water Vapor Diffusion	15. NUMBER OF PAGES 51
				16. PRICE CODE
17. SECURITY CLASSIFICATION OF REPORT UNCLASSIFIED	18. SECURITY CLASSIFICATION OF THIS PAGE UNCLASSIFIED	19. SECURITY CLASSIFICATION OF ABSTRACT UNCLASSIFIED	20. LIMITATION OF ABSTRACT UL	

TABLE OF CONTENTS

	page
LIST OF FIGURES	iv
LIST OF TABLES	v
PREFACE	vi
1. INTRODUCTION	1
2. BACKGROUND	2
3. METHODS AND MATERIALS	6
Methods	6
ASTM E96-80, Procedure B, Upright Cup	6
Limiting Moisture Vapor Transmission Rate Due to Still Air Layer in Cup	7
Conversion of MVTR Values to Resistance Units	9
Sweating Guarded Hot Plate Method	11
Dry Thermal Resistance	12
Water Vapor Permeability	13
Materials	17
Permeable Materials	17
Hydrophobic Membrane Laminates	18
Hydrophilic Membrane Laminates	19
Impermeable Material	20
4. RESULTS AND DISCUSSION	21
Correlation of Upright Cup and Sweating Guarded Hot Plate	21
Effect of High Air Permeability on ASTM E96-80, Procedure B Measurements	24
ASTM E96-80, Procedure BW, Inverted Water Method	25
Evaluation and Ranking Techniques for Hydrophilic Membrane Laminates	26
Comments on Multilayer Clothing Systems Incorporating Hydrophilic Membrane Laminates	28
5. CONCLUSIONS AND RECOMMENDATIONS	30
6. REFERENCES	31
APPENDIX A — Intrinsic Water Vapor Resistance Units	35
APPENDIX B — ASTM E96-80, Procedure B Measurements	39
APPENDIX C — Sweating Guarded Hot Plate Measurements	43

LIST OF FIGURES

Figure		page
1.	Diffusion Through Most Permeable Materials is a Result of Mass Transfer Through Air Spaces	2
2.	Diffusion Behavior Dominated by Air Spaces in Fabric	3
3.	Diffusion Behavior Influenced by Hydrophilic Membranes	4
4.	Variation in Water Vapor Resistance as a Function of Distance From Sample to Water Surface	4
5.	Sample Arrangement for ASTM Method E96-80, Procedure B, Upright Cup Method for Determining Water Vapor Transmission of Materials	6
6.	Diffusion of Water Vapor Through a Stagnant Air Layer	7
7.	Three Resistances to Moisture Vapor Transfer in ASTM E96-80, Procedure B	9
8.	Sweating Guarded Hot Plate	11
9.	Experimental Correlation Between ASTM Method E96-80, Procedure B, and Guarded Sweating Hot Plate	21
10.	Correlation of Intrinsic Water Vapor Resistance Values for ASTM Method E96-80, Procedure B, and Guarded Sweating Hot Plate	22
11.	Correlation of Equivalent Still Air Layer Resistance Values for ASTM Method E96-80, Procedure B, and Guarded Sweating Hot Plate	23
12.	Factors Influencing Anomalous MVTR Values for Two Materials with Identical Air Permeability	24
13.	ASTM E96-80, Procedure BW, Inverted Water Method	25
14.	Water Vapor Resistances Derived from ASTM E96-80, Procedures B and BW Moisture Vapor Transmission Rates	25
15.	Variation of Water Vapor Resistance with Average Water Concentration in Membrane	27
16.	Water Vapor Resistance of Hydrophilic Membrane Laminates Depends on Ambient Humidity and Human Sweating Rate	28
17.	Placement of Hydrophilic Membrane Laminate Affects Water Vapor Resistance of Multilayer Clothing Systems	29

LIST OF TABLES

Table		page
1.	Permeable Materials	17
2.	Hydrophobic Membrane Laminates	18
3.	Hydrophilic Membrane Laminates	19
4.	Impermeable Material	20
B-1	Permeable Materials (Upright Cup Data)	40
B-2	Hydrophobic Membrane Laminates (Upright Cup Data)	41
B-3	Hydrophilic Membrane Laminates (Upright Cup Data)	42
B-4	Impermeable Material (Upright Cup Data)	42
C-1	Permeable Materials (Sweating Hot Plate Data)	44
C-2	Hydrophobic Membrane Laminates (Sweating Hot Plate Data)	45
C-3	Hydrophilic Membrane Laminates (Sweating Hot Plate Data)	46
C-4	Impermeable Material (Sweating Hot Plate Data)	46

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PREFACE

This study was conducted to compare water vapor permeability measurements obtained by two different methods. The two methods were: 1) sweating guarded hot plate, 2) American Society for Testing and Materials (ASTM) Method E96-80, Procedure B. Both methods are in routine use at the U.S. Army Natick Research, Development, and Engineering Center.

John Truong and Marie Jean-Pierre of the Research Section, Materials Research and Engineering Division provided most of the permeable and semipermeable materials used in this study. The moisture vapor transport rate (MVTR) measurements, using ASTM Method E96-80, Procedures B and BW, were performed by Chris Pentheny and Terri Gouveia of the Special Products Section, Materials Research and Engineering Division. Phil Gibson, Research Section, Materials Research and Engineering Division, conducted the sweating guarded hot plate tests.

Several reviewers provided invaluable comments and suggestions during the preparation of this report. They include Ron Segars, Nathan Schneider, Steve Fossey, and Heidi Schreuder-Gibson, all from Natick's Soldier Science Directorate; Don Rivin, Beth Klemperer, Peggy Auerbach, and Gary Olejniczak of the Individual Protection Directorate; and John Breckenridge from the U.S. Army Research Institute of Environmental Medicine.

Comparison of Sweating Guarded Hot Plate and Upright Cup Methods of Measuring Water Vapor Permeability

1. Introduction

The water vapor permeability of clothing materials is a critical property for clothing systems which must maintain thermal equilibrium for the wearer. Clothing materials with high water vapor permeability allow the human body to take advantage of its ability to provide cooling due to sweat production and evaporation. High water vapor permeability is also important in cold environments to prevent or minimize water buildup in clothing.

The water vapor permeability of clothing materials can be measured in a variety of ways. Two common methods are cup/dish tests and sweating hot plate devices.

In general, the cup/dish methods are easy to perform, and use simple and inexpensive equipment. Sweating hot plate methods require much more elaborate equipment and need much larger sample sizes. Sweating guarded hot plate measurements of moisture vapor permeability are often preferred over cup/dish methods since it is thought that the sweating guarded hot plate simulates the heat and mass transfer conditions of the human body fairly accurately.

The objective of the work presented here is to obtain an experimental correlation of these two methods using a wide variety of clothing materials. The materials include a variety of single layer woven and nonwoven fabrics, layered woven and nonwoven fabrics, and semipermeable membrane laminates from different manufacturers.

2. Background

The basic equation for diffusion of one substance through another is given by Fick's Law¹:

$$\frac{\dot{m}}{A} = \frac{D(\Delta c)}{R} \quad (1)$$

\dot{m} = mass flux

A = area

D = diffusion coefficient

Δc = concentration difference

R = resistance to diffusion

For most woven or nonwoven permeable clothing materials, the diffusion constant D in Fick's Law is simply that of water vapor through air. The pathway of moisture vapor diffusion is through the air spaces in the fabric, and the measured resistance to water vapor transfer R is independent of the average water vapor concentration in the sample. The water vapor concentration in the sample is proportional to the average of the relative humidities on both sides of the sample. In most cases, the uptake of water by the textile fibers themselves can be ignored². Exceptions to this would be if excessive swelling of fibers and yarns significantly reduces the free air volume within the fabric or, if one is interested in nonequilibrium water vapor transport, where the initial transport behavior is influenced by fiber water vapor absorption and desorption.^{3,4}

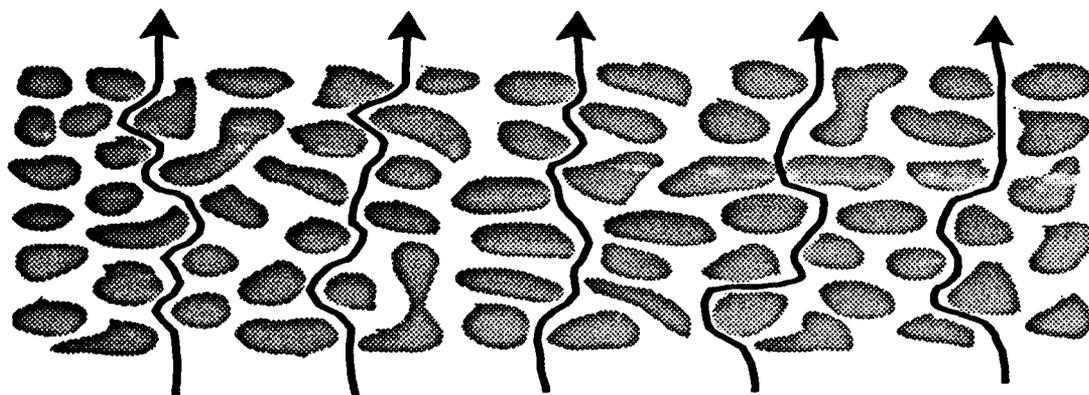


Figure 1. Diffusion Through Most Permeable Materials is a Result of Mass Transfer Through Air Spaces.

There should be good agreement between the relative rankings of all water vapor permeability test methods for permeable clothing materials. There should also be good correlations between the resistances measured by any water vapor permeability test method for these types of permeable clothing materials.

Many so-called "semipermeable" membrane laminates also depend on moisture vapor diffusion through tiny interconnected pores in a membrane⁵⁻⁷. The polymers in these membranes are usually hydrophobic to prevent liquid water from wetting the surface and entering the pores. The measured resistances are again independent of the water vapor concentration in the membrane, and there is good correlation between the measurements done by different methods. Porous membrane laminates and woven and nonwoven permeable fabrics exhibit similar behavior, as shown in Figure 2.

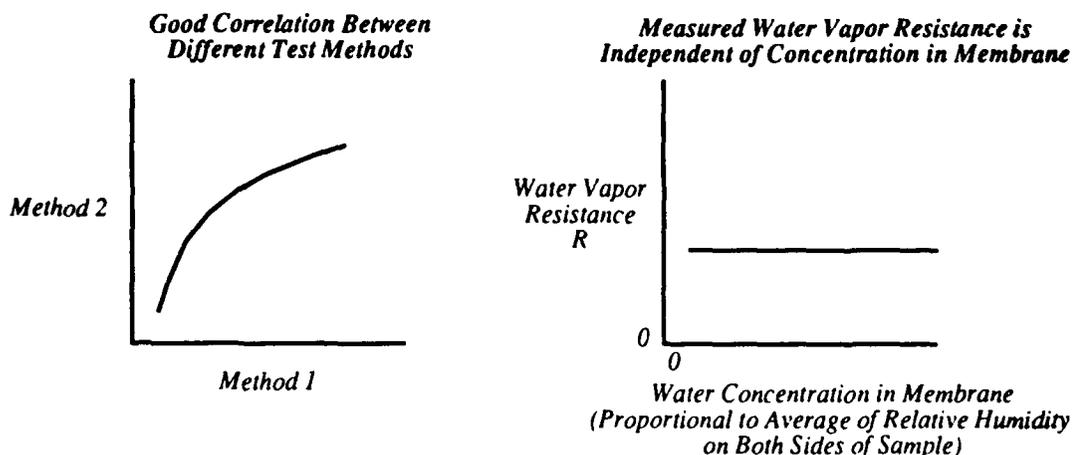


Figure 2. Diffusion Behavior Dominated by Air Spaces in Fabric.

There is a whole class of materials which cannot be assumed to have measured resistances which are independent of the water vapor concentration. These materials incorporate hydrophilic polymers to continuously coat fabrics or semipermeable membrane laminates⁸⁻¹¹. The resulting materials include a monolithic layer, yet still have high moisture vapor transport rates.

The concentration dependence of the diffusion constant in high molecular weight polymers can be very pronounced¹². Fick's Law must be modified so that the expression for the diffusion constant becomes a function of the diffusant concentration:

$$D = D_0 \{1 + f(c)\}, \quad \text{where } c \text{ is average concentration of water in the membrane.} \quad (2)$$

In most moisture vapor permeability tests the concentration in the membrane is related to the relative humidity on both sides of the membrane.

Fick's 1st Law thus becomes:

$$\frac{\dot{m}}{A} = \frac{D_0 \{1 + f(c)\} (\Delta c)}{R} \quad (3)$$

Materials which incorporate hydrophilic membranes behave much differently than materials which depend on transport through air spaces, as shown in Figure 3. There is poor agreement between various test methods, and the measured water vapor resistance is a function of the average relative humidity in the test.

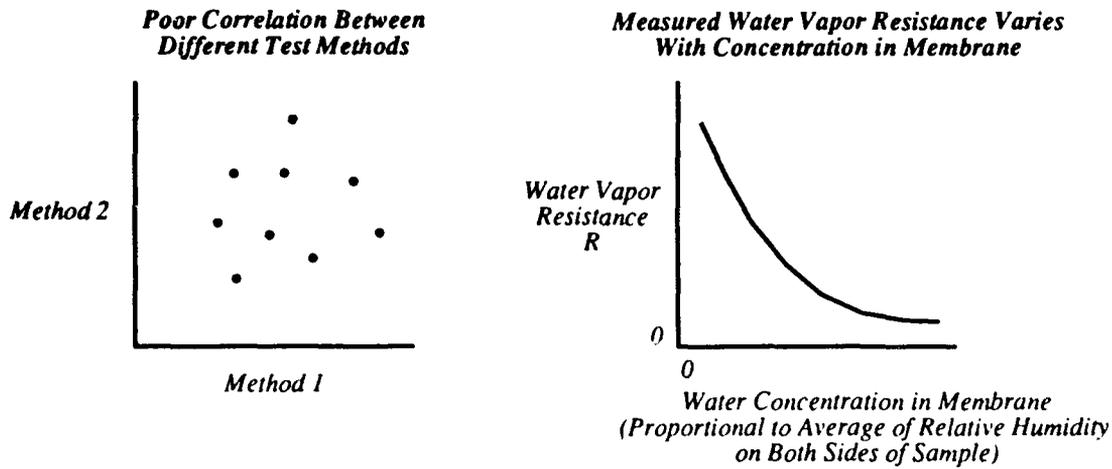


Figure 3. Diffusion Behavior Influenced by Hydrophilic Membranes.

This concentration-dependent diffusion behavior has been noticed in several studies, most notably by Oczevski and Dolhan¹³, and Farnworth, Lotens, and Wittgen¹⁴. The Farnworth, Lotens, and Wittgen study, in particular, nicely illustrates the differences between hydrophobic microporous films and monolithic hydrophilic films.

Figure 4 is adapted from the Farnworth, Lotens and Wittgen study. It illustrates that indeed there is a marked concentration dependence of the measured value of water vapor resistance for materials which incorporate hydrophilic polymers.

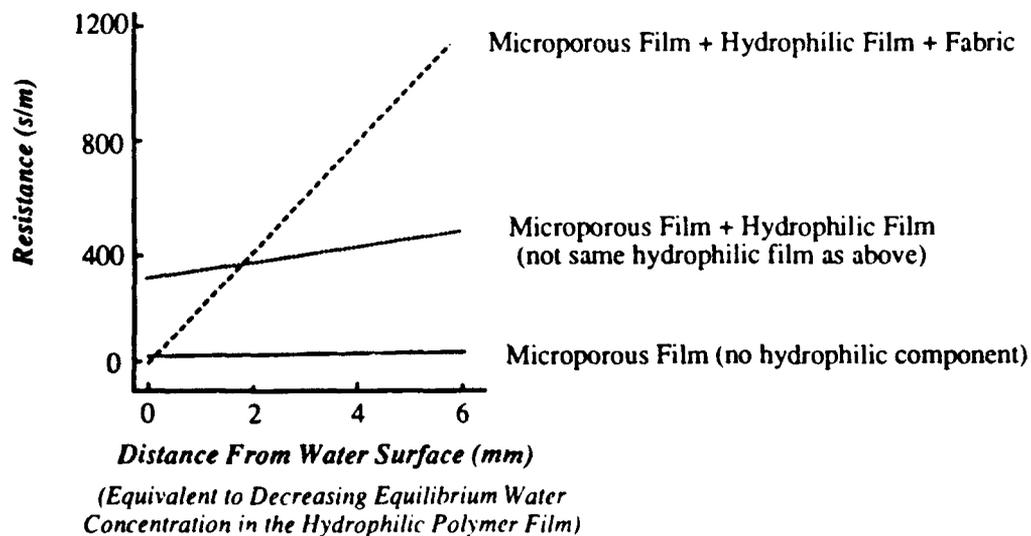


Figure 4. Variation in Water Vapor Resistance as a Function of Distance From Sample to Water Surface. (Adapted from Reference 14)

Most textile materials should thus fall into two distinct classes. Materials that depend on diffusion of water vapor through air spaces should show good correlations between all moisture vapor transmission test methods. The measured water vapor resistance values should also be independent of the conditions used in the test. Materials that incorporate hydrophilic polymer films should show a poor correlation between different water vapor transmission test methods, and the measured water vapor resistance will be dependent upon test conditions, such as relative humidity.

3. Methods and Materials

Descriptions of the two types of water vapor permeability tests (cup/dish and sweating guarded hot plate) follow. These test methods are in routine use at the U.S. Army Natick Research, Development and Engineering Center (Natick). Descriptions of the various materials used for this study are also included in this section.

Methods

ASTM E96-80, Procedure B, Upright Cup

The American Society for Testing and Materials (ASTM) publishes standard test methods for water vapor transmission properties of materials¹⁵. The standard condition used most extensively at Natick is Procedure B - Water Method at 23°C (73.4°F). A schematic of this test method is shown below.

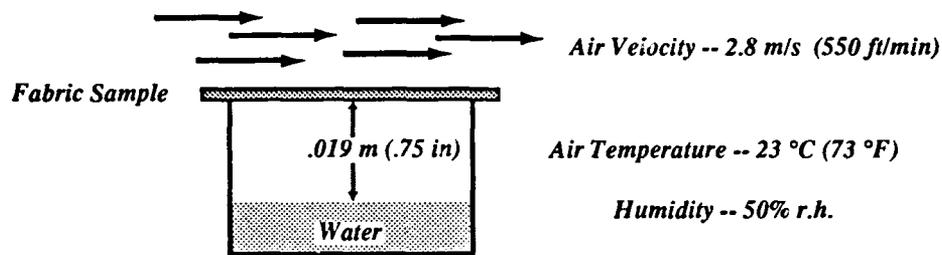


Figure 5. Sample Arrangement for ASTM Method E96-80, Procedure B, Upright Cup Method for Determining Water Vapor Transmission of Materials.

The reported quantity from this test is the Moisture Vapor Transmission Rate (MVTR), in $\text{g}\cdot\text{m}^2/24 \text{ h}$, which is determined from periodic weighings of the sample dish. Although the ASTM Method E96-80 calls for reporting units of $\text{g}\cdot\text{m}^2/\text{h}$, it is standard practice at Natick to use the longer time period of 24 hours.

This particular ASTM Method E96-80, Procedure B, although widely used, has some inherent problems. Most importantly, the still air layer between the fabric sample and the water surface has a high resistance to moisture vapor transmission. This still air layer often has a higher water vapor resistance than the fabric itself. There are a variety of other methods, well documented in the literature, which are perhaps more appropriate for determining the water vapor resistance of textile materials. These methods may be found in references 16-23. The ASTM Method E96-80 is most suitable for materials which have high water vapor resistances. The ASTM Method E96-80 continues to be used, however, because of its widespread acceptability, convenience, and large existing database of previous results.

The MVTR values generated with ASTM E96-80 Procedure B include the effect of the resistances of the air layers both above and below the sample. However, these resistances are not subtracted out in the reported data. It is desirable to determine the intrinsic properties of the textile material alone, by accounting for the existence of the air layers in some way. In order to accomplish this, it is possible to convert the MVTR values obtained from the ASTM E96-80 test to water vapor resistance values, which are independent of test conditions for nonhydrophilic porous materials. Resistance values are convenient since they may be added in series to determine the overall properties of layers of materials.

The next two sections deal with establishing an upper limit for the MVTR values in the ASTM E96-80 Procedure B test, and with developing a simple way to convert MVTR values to resistance units.

Limiting Moisture Vapor Transmission Rate Due to Still Air Layer in Cup

The ASTM E96-80 Procedure B test includes a layer of still air under the fabric sample. This still air layer of 1.9 cm (0.75 inch) imposes an upper limit on the measurable moisture vapor transport rate. As long as the fabric prevents significant air penetration into the cup, the air layers remain stagnant, and the limiting moisture vapor transmission rate as determined by this still air layer may be calculated.

The air layer between the surface of the water and the fabric is thin enough so that convective mass transfer is suppressed. Convection at this temperature would not occur until the thickness of the still air layer is appreciably greater than two centimeters²⁴. Mass transfer through this still air layer is assumed to proceed by pure diffusion.

Diffusion through a stagnant air layer is well understood. The isothermal evaporation of water and diffusion through a stagnant air layer can be described by Stefan's Law²⁵ (equation 4), and is illustrated in Figure 6.

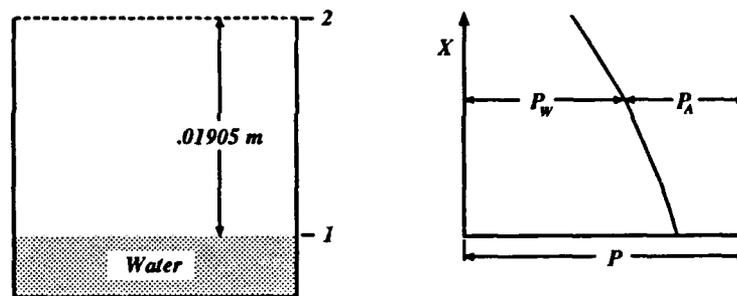


Figure 6. Diffusion of Water Vapor Through a Stagnant Air Layer (adapted from Reference 25).

$$\dot{m}_{total} = - \left(\frac{DM_w A}{R_0 T} \right) \left(\frac{p}{p - p_w} \right) \left(\frac{dp_w}{dx} \right) \quad (4)$$

\dot{m}_{total} = total mass flow of water vapor through air layer of thickness δx

D = diffusion coefficient of water in air (0.256 cm²/sec)

p = absolute air pressure (1.01326 x 10⁵ N/m²)

M_w = molecular weight of water (18 g/mole)

A = area (m²)

R_0 = universal gas constant (8315 N-m/kg-mole-K)

T = temperature in degrees K

p_w = partial pressure of the water vapor

p_A = partial air pressure

dx = air layer thickness

Stefan's Law may be integrated to obtain the total mass flux of water between the water surface and the top of the cup:

$$\dot{m}_{w\text{total}} = \int_{p_{w1}}^{p_{w2}} \left(\frac{DM_w A}{R_0 T} \right) \left(\frac{p}{p - p_w} \right) \left(\frac{dp_w}{\delta x} \right) \quad (5)$$

$$\dot{m}_{w\text{total}} = \frac{DpM_w A}{R_0 T(x_2 - x_1)} \ln \frac{p - p_{w2}}{p - p_{w1}} = \frac{DpM_w A}{R_0 T(x_2 - x_1)} \ln \frac{p_{A2}}{p_{A1}} \quad (6)$$

$\delta x = x_2 - x_1 =$ distance from water surface to top of cup (0.01905 m)
 $p_{w1} =$ saturated water vapor pressure at water surface ($0.0028366 \times 10^6 \text{ N/m}^2$)
 $p_{w2} =$ partial water vapor pressure at the top of the cup = ϕp_{w1} , where ϕ is relative humidity (0.50), so $p_{w2} = 0.0014183 \times 10^6 \text{ N/m}^2$
 $p_{A1} = p - p_{w1}$ ($9.848 \times 10^4 \text{ N/m}^2$)
 $p_{A2} = p - p_{w2}$ ($9.991 \times 10^4 \text{ N/m}^2$)

$$\frac{\dot{m}_{w\text{total}}}{\text{m}^2} = \frac{(0.256 \times 10^{-4} \text{ m}^2/\text{s})(1.013 \times 10^5 \text{ N/m}^2)(18 \text{ g/mole})}{(296 \text{ K})(8315 \text{ N} \cdot \text{m}/\text{kg} \cdot \text{mole} \cdot \text{K})(0.01905 \text{ m})} \left[\ln \frac{9.99 \times 10^4 \text{ N/m}^2}{9.84 \times 10^4 \text{ N/m}^2} \right] \quad (7)$$

$$\frac{\dot{m}_{w\text{total}}}{\text{m}^2} = 1.425 \times 10^{-5} \text{ kg/s} = 1231 \text{ g/24 h} \quad (8)$$

$$MVTR = 1230 \text{ g} \cdot \text{m}^2 / 24 \text{ h} \quad (9)$$

This is the highest moisture vapor transport rate possible (assuming still air conditions underneath the fabric) in the ASTM E96-80 Procedure B test. As will be shown later, the assumption of still air conditions is a good one for fabrics with low to moderate air permeability values. The still air assumption is not valid for fabrics with very high air permeability since the external air flow begins to penetrate through the fabric into the cup.

Conversion of MVTR Values to Resistance Units

The moisture vapor transmission rate measured in the ASTM E96-80 Procedure B Method is a result of the sum of three resistances, as shown in Figure 7.

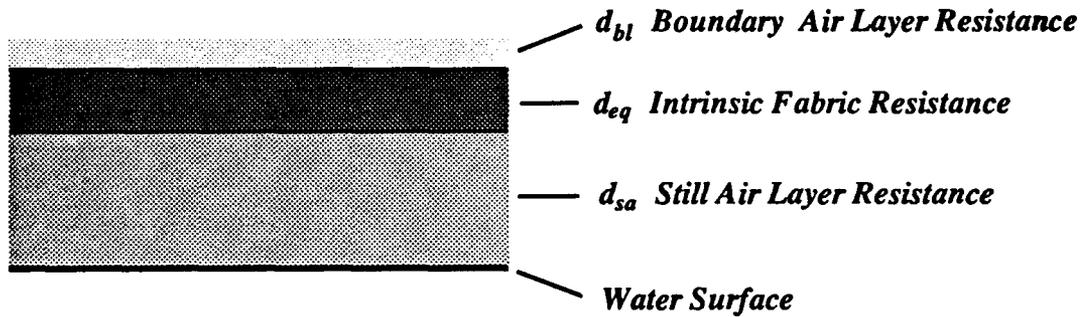


Figure 7. Three Resistances to Moisture Vapor Transfer in ASTM E96-80 Procedure B.

One can define the intrinsic resistance of the material in terms of the equivalent thickness of still air. This works well as long as the transport properties are dependent on diffusion of water vapor through air spaces in the material.

Fick's Law may be written as:

$$d_{total} = \left(\frac{1}{\dot{m}} \right) D(\Delta c)A \quad (10)$$

d_{total} = total resistance of the system ($d_{sa} + d_{eq} + d_{bl}$) in cm of still air

\dot{m} = mass flux of water vapor, g / s

D = diffusion coefficient of water vapor in air, cm^2 / s

Δc = concentration difference, g / cm^3

A = Area, cm^2

As noted by Fourt and Harris¹⁷, the concentration difference Δc can be obtained from the relation:

$$\Delta c = \Delta p M_w / RT = (2.89 \times 10^{-4})(\Delta p / T) \quad (11)$$

Δc = concentration difference (g/ cm^3)

Δp = vapor pressure difference (mmHg)

M_w = molecular weight of water (18 g/mole)

R = gas constant

T = absolute temperature (K)

The equation for the intrinsic fabric resistance becomes:

$$d_{eq} = \left(\frac{1}{\dot{m}}\right) D (2.89 \times 10^{-4}) \left(\frac{\Delta p}{T}\right) A - d_{sa} - d_{bl} \quad (12)$$

The resistance of the still air layer underneath the fabric is found simply from its thickness in cm, so for the ASTM E96-80, Procedure B:

$$d_{sa} = 1.905 \text{ cm} \quad (13)$$

Finding the resistance of the outer boundary air layer presents a more difficult problem. Work conducted by Turl¹⁶ determined the equivalent resistance as a function of air flow velocity, but the boundary layer thickness d_{bl} is greatly affected by the flow conditions, which are not the same as in Turl's study. Because the ASTM E96-80 Procedure B method uses an air flow of 2.8 m/s (550 ft/min), the equivalent thickness of the outer boundary air layer should be quite small (less than 0.3 cm). It will not be accounted for explicitly and is therefore included in the value for d_{eq} . This outer boundary air layer resistance, which is highly sensitive to air velocity and direction, is an obvious source of data scatter.

For the ASTM E96-80 Procedure B test, the appropriate values for the variables in the equation for intrinsic fabric resistance are:

$$\begin{aligned} D &= 0.256 \text{ cm}^2/\text{s} \\ \Delta p &= 10.65 \text{ mmHg} \\ T &= 296 \text{ K} \\ d_{sa} &= 1.905 \text{ cm} \end{aligned}$$

The equation for the equivalent air resistance of the fabric alone can be expressed in terms of the measured MVTR and the air layer resistances as:

$$d_{eq} = \left(\frac{2300}{MVTR}\right) - d_{sa} \quad \text{or equivalently,} \quad d_{eq} = \left(\frac{2300}{MVTR}\right) - 1.9 \quad (14)$$

d_{eq} = intrinsic fabric resistance, in cm of still air (includes boundary layer, d_{bl})
 $MVTR$ = moisture vapor transmission rate, $\text{g}\cdot\text{m}^2/24 \text{ h}$, ASTM E96-80, Procedure B

The intrinsic fabric resistance R_f may also be expressed in resistance units of s/cm through the relation:

$$R_f = \frac{d_{eq}}{D} \quad (15)$$

Sweating Guarded Hot Plate Method

The general principles of a guarded hot plate apparatus may be found in Reference 26. 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.

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 moisture vapor transmission properties. Figure 8 shows a schematic of the sweating guarded hot plate apparatus.

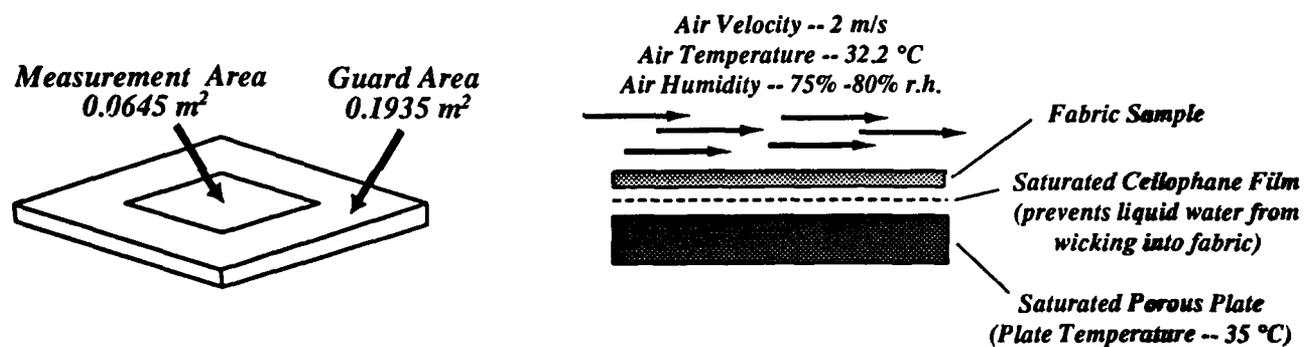


Figure 8. Sweating Guarded Hot Plate.

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:

$$R_{total} = \frac{A(T_{plate} - T_{air})}{Q} \quad (16)$$

- 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 $0.155 \text{ }^\circ\text{C}\cdot\text{m}^2/\text{watt}$)
- A given in m^2
- T_{plate} and T_{air} given in $^\circ\text{C}$
- 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:

$$R_i = R_{total} - R_0 \quad (17)$$

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. Woodcock²⁷ 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.

$$i_m = \frac{\left\{ \frac{(Q)(R_{total})}{A} \right\} - (T_{plate} - T_{air})}{S(p_s - \phi p_a)} \quad (18)$$

- 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 m²

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.

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 importance of the term i_m/clo is illustrated if the equations for dry heat transfer (E_{dry}), and evaporative heat transfer (E_{evap}), are written:

$$E_{dry} \text{ (watts / m}^2\text{)} = \left(\frac{6.45}{clo} \right) (\Delta T) \quad (19)$$

$$E_{evaporative} \text{ (watts / m}^2\text{)} = i_m \left(\frac{6.45}{clo} \right) S (\Delta p) \quad (20)$$

$$\text{Total Heat Transfer (watts / m}^2\text{)} = \left(\frac{6.45}{clo} \right) (\Delta T) + 14.2 \left(\frac{i_m}{clo} \right) (\Delta p) \quad (21)$$

ΔT = temperature difference, °C

S = Lewis Relation (2.2 °C/mmHg)

Δp = vapor pressure difference, mmHg

clo = R_{total} in clo units

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.

Note that these values include the effects of the boundary air layer over the sample. It is desirable to obtain intrinsic properties of the materials, such as intrinsic thermal resistance and intrinsic water vapor resistance. Such a system of intrinsic units is available in the draft standard German Deutsches Institut für Normung (DIN) Standard 54-101²⁸, and is also described in a NATO publication²⁹.

Details concerning the derivation of the intrinsic units R_{ei} and R_{ei0} may be found in Appendix A. The intrinsic unit R_{ei} for water vapor resistance can be found from the values of R_{total} (clo) and i_m as shown below:

$$R_{ei} = 0.0929 \left\{ \frac{1}{(i_m / clo)} - \frac{1}{(i_{m0} / R_0)} \right\} \quad (22)$$

R_{ei} = intrinsic water vapor resistance, $m^2 \cdot mbar / watt$
 i_{m0} = bare plate i_m value
 R_0 = bare plate thermal resistance, clo units

This intrinsic resistance, R_{ei} , is analogous to the intrinsic resistance obtained in the previous section on the ASTM E96-80, Procedure B, Upright Cup Method.

A moisture vapor transmission rate may also be defined for the sweating guarded hot plate³⁰.

$$WVT = \frac{1}{(R_{ei} + R_{ei0})(\Delta H_{vap})} \quad (23)$$

R_{ei} = intrinsic water vapor resistance, $watt \cdot m^2 / mbar$
 R_{ei0} = water vapor resistance of boundary layer on bare plate, $watt \cdot m^2 / mbar$
 ΔH_{vap} = latent heat of vaporization at sweating guarded plate temperature ($35^\circ C$)
 $= 0.672$ $watt \cdot h / g$
 WVT = water vapor transmission, $g / m^2 \cdot h \cdot mbar$

For a water vapor pressure difference Δp between the plate surface and the ambient atmosphere, the MVTR as measured with the plate is given by:

$$MVTR_{plate} = (WVT)(24 h)(\Delta p) \quad , \text{ in units of } g \cdot m^2 / 24 h \quad (24)$$

The test conditions used in this study resulted in a Δp of 17.7 mbar:

$$MVTR_{plate} = 424.8(WVT) \quad (25)$$

In terms of i_m / clo , the moisture vapor transmission rate may be written as:

$$MVTR_{plate} = 6806 \left(\frac{i_m}{clo} \right) \quad , \text{ in units of } g \cdot m^2 / 24 h \quad (26)$$

It is desirable to obtain resistance values from the sweating guarded hot plate test which are in the same units as the resistance values for the upright cup test. This can be done by combining equation 26 (for the value of $MVTR_{plate}$) with equation 12 to come up with the expression

$$d_{eq} = \frac{1.27 \times 10^5}{(i_m / clo)} \left(\frac{D \Delta p}{T} \right) \quad (27)$$

d_{eq} = intrinsic fabric resistance, in cm of still air (includes boundary air layer resistance)
 i_m / clo = measured i_m / clo value in the sweating guarded hot plate test

For the test conditions used in this study, where the plate temperature was 35°C, and the air temperature was 32.2°C at 75% to 80% relative humidity,

$T = 307$ K (average of plate and air temperatures)

$D = 0.271$ cm²/s (at $T=307$ K)

$\Delta p = 13.3$ mmHg (17.7 mbar)

Equation 14 for the upright cup, and equation 27 for the sweating guarded hot plate, allow the resistance values to be expressed in an identical system of units, which should make determining the correlation between the two methods more straightforward.

Materials

The materials chosen for this study can be divided into four classes: 1) Permeable, 2) Hydrophilic membrane laminates, 3) Hydrophobic membrane laminates, and 4) Impermeable. Many of these materials are under development for military applications and are not commercially available. Measured properties for these materials are listed in Appendices B and C. Applicable military specification identifications for several standard fabrics are included in the references. Further information on many of the semipermeable membranes, such as manufacturer and physical property data, may be found in reference 7.

Permeable Materials

The permeable materials include both woven and nonwoven materials. Some of the materials are multilayer laminates, which have been either adhesively bonded or are laid over the top of each other.

Table 1. Permeable Materials

Sample #	Configuration	Materials
1	Single Layer	Water-Repellent Treated Nylon/Cotton Woven Fabric ³¹
2	Single Layer	Water-Repellent Treated Nylon/Cotton Twill Woven Fabric ³²
3	Single Layer	Nonwoven Fabric Coated with Activated Carbon, Scrim Backing
4	2 Layer Laminate	Carbon-Loaded Polyurethane Foam Laminate (90 mil thick) ³³
5	2 Layer Laminate	Carbon-Loaded Polyurethane Foam Laminate(50 mil thick)
6	3 Layer Laminate	Kevlar® Shell, Activated Carbon Cloth, Nomex®Liner Fabric
7	2 Layers	Sample #1 and Sample #5 Combined
8	2 Layers	Sample #2 and Sample #5 Combined
9	2 Layers	Sample #1 and Sample #4 Combined
10	2 Layers	Sample #2 and Sample #4 Combined

Hydrophobic Membrane Laminates

These materials, often termed "semipermeable" membranes, are made of a hydrophobic polymer containing tiny interconnected pores, which allow water vapor to diffuse through the membrane. Most of these membranes have been laminated to a shell fabric and are often also laminated to an inner liner fabric.

Table 2. Hydrophobic Membrane Laminates

Sample #	Configuration	Materials
11	2 Layer Laminate	Nylon/Cotton Shell Plastolon® Membrane (Polytetrafluoroethylene--PTFE)
12	2 Layer Laminate	Nylon Taffeta Shell Tetratex® Membrane (PTFE)
13	2 Layer Laminate	Nomex® Shell Empore® Membrane (Carbon-Loaded PTFE)
14	3 Layer Laminate	Nylon Taslan® Shell Plastolon® Membrane (PTFE) Nylon Tricot Knit Liner
15	3 Layer Laminate	Nylon Taslan® Liner Celgard® 2500 Membrane (isotactic polypropylene) Nylon Tricot Knit Liner
16	3 Layer Laminate	Nylon Taslan® Shell Repel® Membrane (acrylic fluoropolymer) Nylon Tricot Knit Liner
17	3 Layer Laminate	Nomex® Shell Repel® Membrane (acrylic fluoropolymer) Nylon Tricot Knit Liner
18	3 Layer Laminate	Nylon/Cotton Shell Repel® Membrane (acrylic fluoropolymer) Nylon Tricot Knit Liner
19	3 Layer Laminate	Nylon Taslan® Shell Empore® Membrane (Carbon-Loaded PTFE) Nylon Tricot Knit Liner

Hydrophilic Membrane Laminates

These membranes contain a monolithic hydrophilic polymer coating or layer. They may also contain a porous hydrophobic membrane as a support for the hydrophilic layer.

Table 3. Hydrophilic Membrane Laminates

Sample #	Configuration	Materials
20	2 Layer Laminate	Nomex®Shell Hypermem®Membrane (coextruded polyether/polyester)
21	3 Layer Laminate	Taslan®Nylon Shell Thintech®Membrane (polyethylene/polyurethane) Nylon Tricot Knit Liner
22	3 Layer Laminate	Nomex®Shell Sympatex®Membrane (co-polyether-polyester) Nomex®Jersey Knit Liner
23	3 Layer Laminate	Taslan®Nylon Shell Sympatex®Membrane (co-polyether-polyester) Nylon Tricot Knit Liner
24	3 Layer Laminate	Nomex®Shell Gore-Tex®II Membrane (PTFE/polyurethane/polyalkylene oxide) Nomex®Jersey Knit
25	3 Layer Laminate	Nomex®III Shell Gore-Tex®II Membrane (PTFE/polyurethane/polyalkylene oxide) Nomex®Jersey Knit
26	3 Layer Laminate	Taslan®Nylon Shell Gore-Tex®II Membrane (PTFE/polyurethane/polyalkylene oxide) Nylon Tricot Knit Liner
27	3 Layer Laminate	Taslan®Nylon Shell Gore-Tex®II Membrane (PTFE/polyurethane/polyalkylene oxide) Nylon Tricot Knit Liner

Impermeable Material

One impermeable material is included to illustrate the full range of material behavior.

Table 4. Impermeable Material

Sample #	Configuration	Materials
28	Single Layer	Butyl-Coated Nylon Cloth ³⁴

4. Results and Discussion

Correlation of Upright Cup and Sweating Guarded Hot Plate

A general correlation between the upright cup and the guarded sweating hot plate is shown in Figure 9. The two measurements shown are the Moisture Vapor Transmission Rate (for the upright cup method) and the i_m/clo values (for the sweating guarded hot plate). The additional upper horizontal axis shows the corresponding moisture vapor transmission rate calculated for the guarded sweating hot plate.

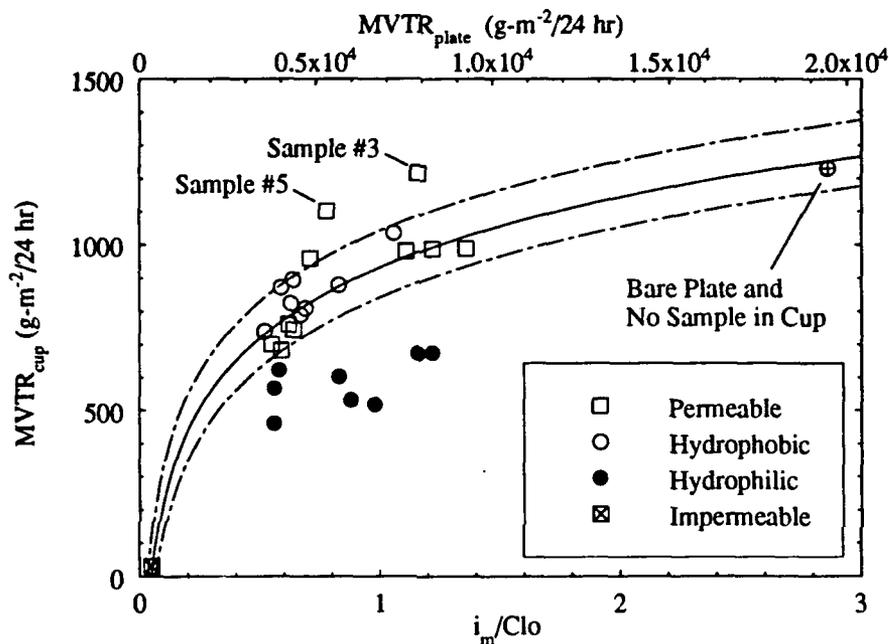


Figure 9. Experimental Correlation Between ASTM Method E96-80, Procedure B, and Guarded Sweating Hot Plate. Data in Appendices B and C.

It is clear that there is a fairly good correlation between the two test methods for materials whose properties depend on water vapor diffusion through air passages in the structure. Nearly all the permeable and hydrophobic membrane laminates lie within the 95% confidence limits shown in Figure 9. The exceptions are Sample #3 and Sample #5, which have anomalously high *MVTR* values. It will be shown later that the very high air permeability of these particular materials allows the 550 ft/min air flow over the cup to begin penetrating through the fabric into the cup, disturbing the still air diffusion conditions and enhancing the moisture vapor transfer rate.

Figure 9 also shows that all the hydrophilic membrane laminates show no correlation between the two test methods. The hydrophilic materials exhibit much better water vapor transmission properties in the sweating guarded hot plate test than they do in the upright cup test. As discussed in the Methods section of this report, the test conditions in the guarded sweating hot plate test result in a much higher equilibrium water content in the hydrophilic polymer layer, which changes the polymer's permeability, thereby greatly increasing the water vapor transport rate through the membrane.

The quantities shown in Figure 9 are both essentially measurements of the mass flux of water vapor which passes through the material. Both the $MVTR$ values and the i_m/clo values include the various air layer resistances present in the two tests.

The Methods and Materials section of this report derived relations which allow the intrinsic water vapor resistance to be calculated from $MVTR$ and i_m/clo measurements. Intrinsic fabric water vapor resistances are convenient since they may be added in series to determine the overall resistance of combined layers of fabrics, using only the measured resistances of the individual layers. The intrinsic water vapor resistance of a material is also closer to being a fundamental material property than quantities such as $MVTR$ or i_m/clo , which are both highly dependent on the test conditions.

There should also be a direct linear correlation between the intrinsic fabric resistances as measured by the two methods, except for materials with concentration-dependent water vapor resistances. Intrinsic fabric water vapor resistances determined by the two test methods are shown in Figure 10.

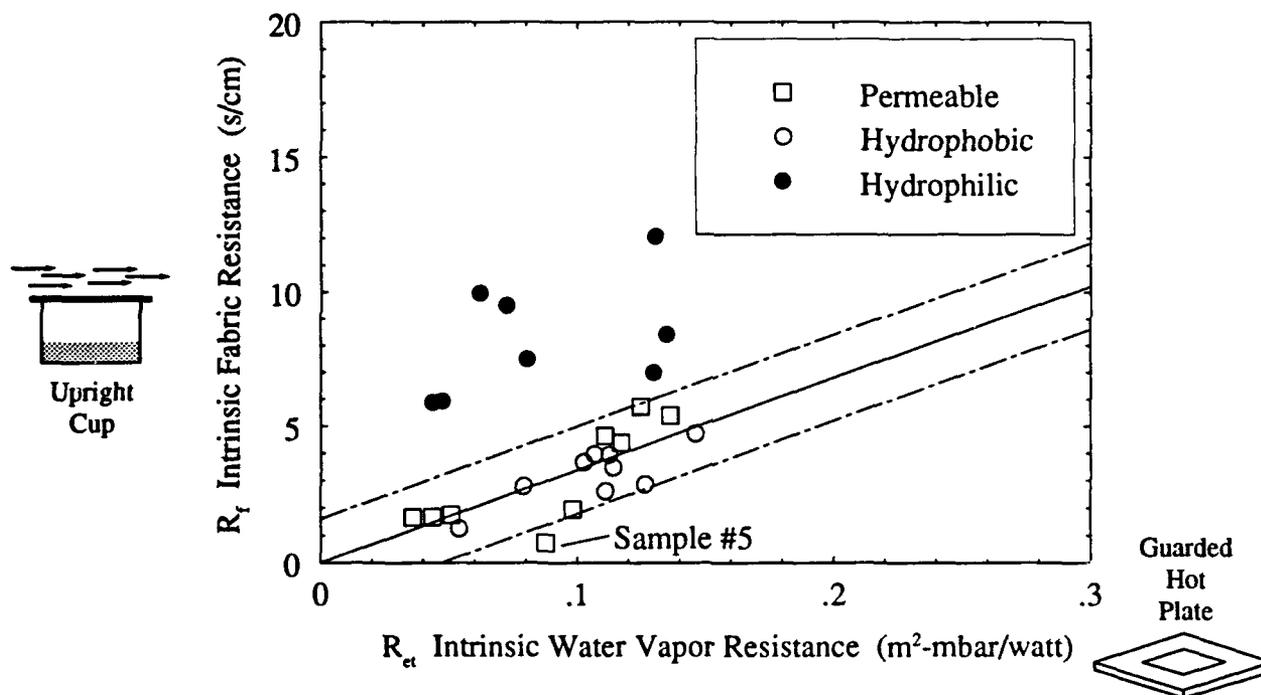


Figure 10 shows the correlation between the two types of tests, but the intrinsic resistance units are different, which makes the comparison rather confusing. Equation 27 presented a way to convert i_m/clo values for the sweating guarded hot plate to an equivalent still air resistance, as presented in Figure 11. In Figure 11, the boundary air layer resistances are included in the equivalent still air layer resistance values for both the upright cup and sweating guarded hot plate.

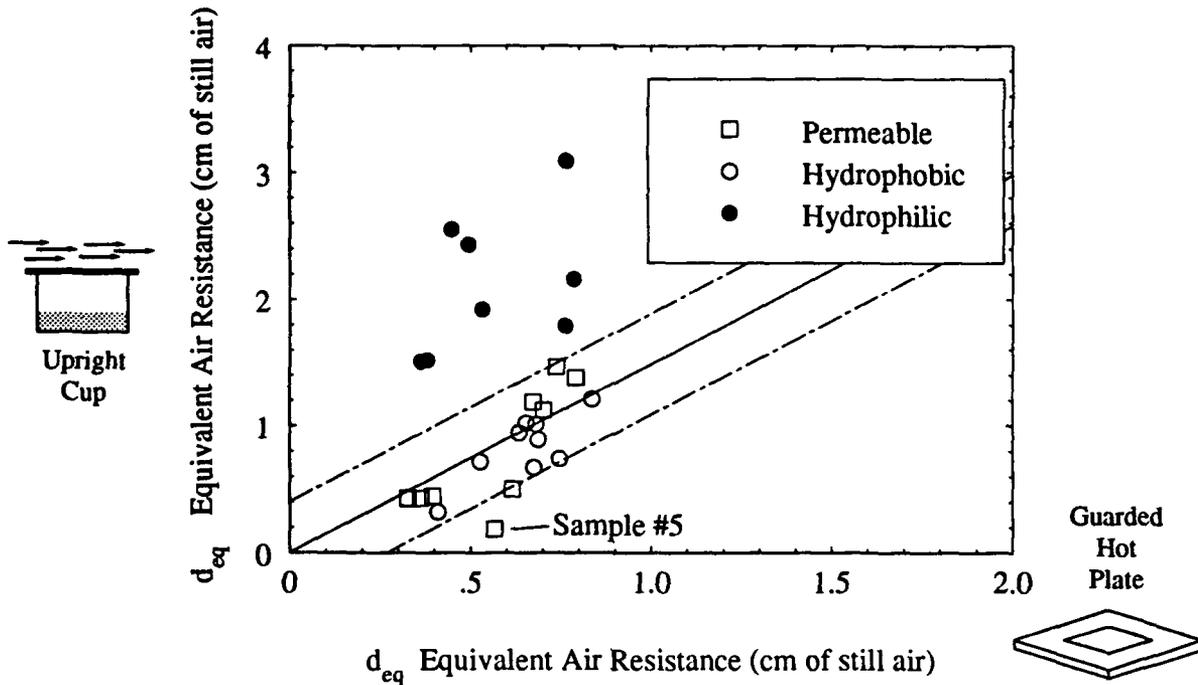


Figure 11. Correlation of Equivalent Still Air Layer Resistance Values for ASTM Method E96-80, Procedure B, and Guarded Sweating Hot Plate. Data from Appendices B and C.

There are two reasons that the linear correlation for the permeable and hydrophobic membrane materials does not have a slope of one. First, the boundary air layer resistances, which are included in Figure 11, are different for each test due to the differing wind speeds over the sample (although the difference is only 0.8 m/s). Second, mass transport in the upright cup test occurs due to diffusion driven only by a concentration gradient. Mass transport in the sweating guarded hot plate test proceeds via both diffusion and convection, since there is a temperature difference between the plate surface and the ambient air. If the plate surface were to be maintained at the ambient air temperature, and if the boundary air layer resistances were subtracted out from the data, the linear correlation between the data in Figure 11 would presumably have a slope of one.

Figures 9, 10, and 11 indicate that the ASTM E96-80, Procedure B upright cup method is adequate for screening most materials dependent upon water vapor diffusing through the air spaces in their structure. However, the upright cup method gives anomalous results for materials which incorporate monolithic hydrophilic polymer layers, and for materials with high air permeabilities. Both cases are discussed in the next two sections.

Effect of High Air Permeability on ASTM E96-80, Procedure B Measurements

Materials with high air permeabilities may allow the external air flow to penetrate through the sample and disturb the still air layer between the water surface and the sample. Whether penetration occurs is not just a function of air permeability, but also depends on factors such as average diameter of the pores, the material's thickness, and the tortuosity of the passages through the material. Some of these effects are shown schematically in Figure 12.

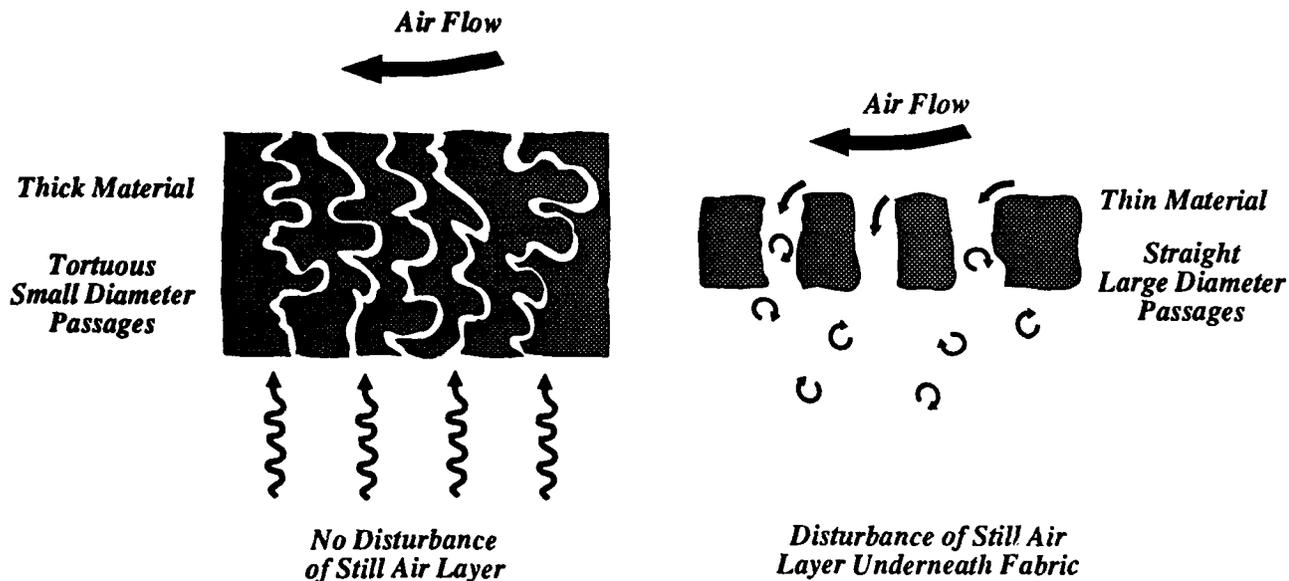


Figure 12. Factors Influencing Anomalous MVTR Values for Two Materials with Identical Air Permeability.

The disturbance of the still air layer means that the nature of the test has changed. Since the upper limit of *MVTR* allowed by the still air layer is approximately $1200 \text{ g}\cdot\text{m}^{-2}/24 \text{ h}$ in the ASTM E96-80, Procedure B test, it's clear that the resistance of the air layer within the cup is changing in some undefined way. In fact, if one calculates the intrinsic fabric resistance ($d_{e,q}$ or R_p) of sample #3, it turns out to be a negative number, which is clearly unreasonable.

Sample #5, which also exhibited this type of behavior, was tested in combination with two different cover fabrics (samples #7 and #8). The cover fabrics eliminated the air penetration into the still air layer, and the results for samples #7 and #8 fall onto the expected curves in Figures 9, 10, and 11. If sample #5 really did have some fundamentally different water vapor transport mechanism, it would also be evident in the results for samples #7 and #8

Materials with *MVTR* values greater than $1200 \text{ g}\cdot\text{m}^{-2}/24 \text{ h}$ should be regarded with skepticism. Such high values indicate air flow penetration into the still air layer under the fabric, making it difficult to compare results between different materials, since intrinsic fabric properties are no longer being measured.

ASTM E96-80, Procedure BW, Inverted Water Method

The deficiencies of the upright cup method for hydrophilic membranes have been recognized for some time. An alternate procedure BW in ASTM E96-80 inverts the cup so that the water is in direct contact with the sample. A schematic of Procedure BW is given in Figure 13.

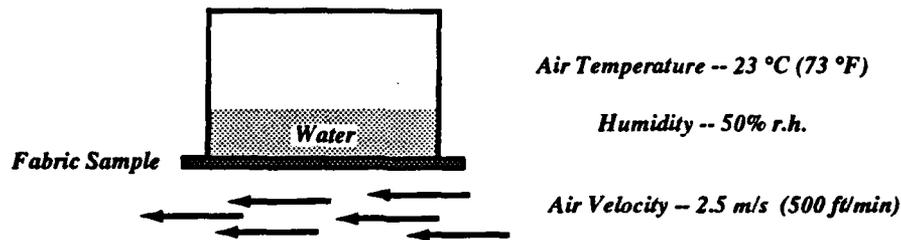


Figure 13. ASTM E96-80, Procedure BW, Inverted Water Method.

Procedure BW results in a much higher equilibrium water content in the hydrophilic polymer layer. The diffusion constant increases, dramatically lowering the measured water vapor resistance. In addition, the still air layer resistance underneath the fabric is eliminated.

The intrinsic fabric water vapor resistance d_{eq} can be calculated for both Procedure B and BW and plotted as a function of distance from the water surface.

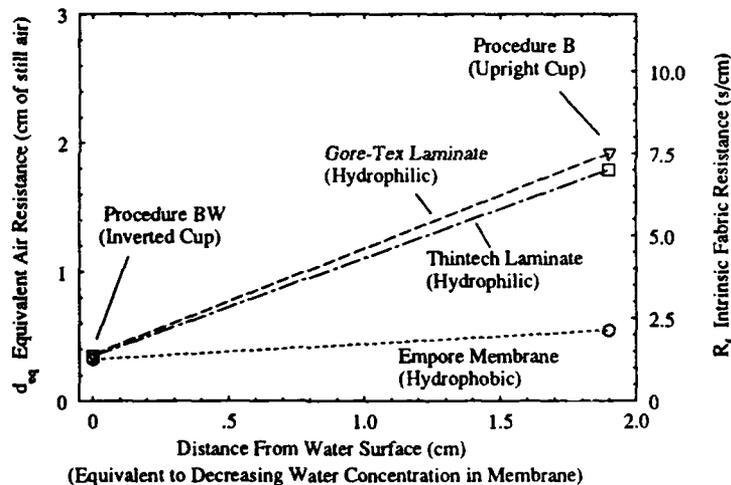


Figure 14. Water Vapor Resistances Derived from ASTM E96-80, Procedures B and BW Moisture Vapor Transmission Rates.

This figure is essentially identical to Figure 4, which shows results from the Farnworth, Lotens, and Wittgen study¹⁴. The hydrophobic membrane's properties change very little between Procedure B and BW. The resistance of the two hydrophilic membrane laminates, which are approximately the same as the hydrophobic membrane in Procedure BW, become four times larger when measured under the conditions present in Procedure B. Note that neither Procedure B or BW is representative of actual use conditions. Procedure B tests hydrophilic membranes in fairly dry conditions, which makes them look disproportionately poor compared to other materials. Procedure BW tests the membrane in contact with liquid water and under a pressure head due to the weight of water in the cup. Procedure BW tends to make the hydrophilic membranes look a little better than they really are, since actual use conditions do not allow liquid water under pressure to come in contact with the inner surface of clothing.

Evaluation and Ranking Techniques for Hydrophilic Membrane Laminates

Minimum moisture vapor transmission rates (ASTM E96-80, Procedures B and BW) are incorporated into the military specifications for components of several U.S. Army uniforms and equipment systems³⁵⁻³⁹ which include semipermeable membranes. These measurements are used for quality control purposes. The two measurements give a good indication if a particular lot of material will provide equivalent water vapor permeability as compared to another lot of material.

For many materials, ASTM E96-80, Procedure B and BW, will also be sufficient to rank the water vapor permeability of new candidate materials with respect to standard materials used in present uniform and equipment items. Procedures B and BW represent the two environmental extremes for semipermeable membrane laminates, particularly for monolithic hydrophilic membranes. Procedure BW, the inverted cup method, represents the condition of having a high average water concentration in the membrane. Procedure B, the upright cup method, represents the condition of a low average water concentration in the membrane.

As long as one semipermeable membrane laminate exhibits a higher MVTR in both the inverted and upright cup tests, it is safe to say that the material will have a higher moisture vapor permeability over the range of actual use conditions present in a clothing system.

Unfortunately, when materials are compared to each other using both Procedure B and BW, the ranking of materials can flip-flop. That is, a material with the higher MVTR in the inverted cup can have the lowest MVTR in the upright cup test. One must then decide which test is more representative of actual field use conditions, or whether another test condition would be more representative of actual field use conditions.

Figure 15 illustrates how the degree of dependence of the apparent diffusion constant of a semipermeable membrane can complicate the evaluation or ranking of one material compared to another. Figure 15 shows the intrinsic water vapor resistance as a function of distance from the water surface for three different semipermeable membranes.

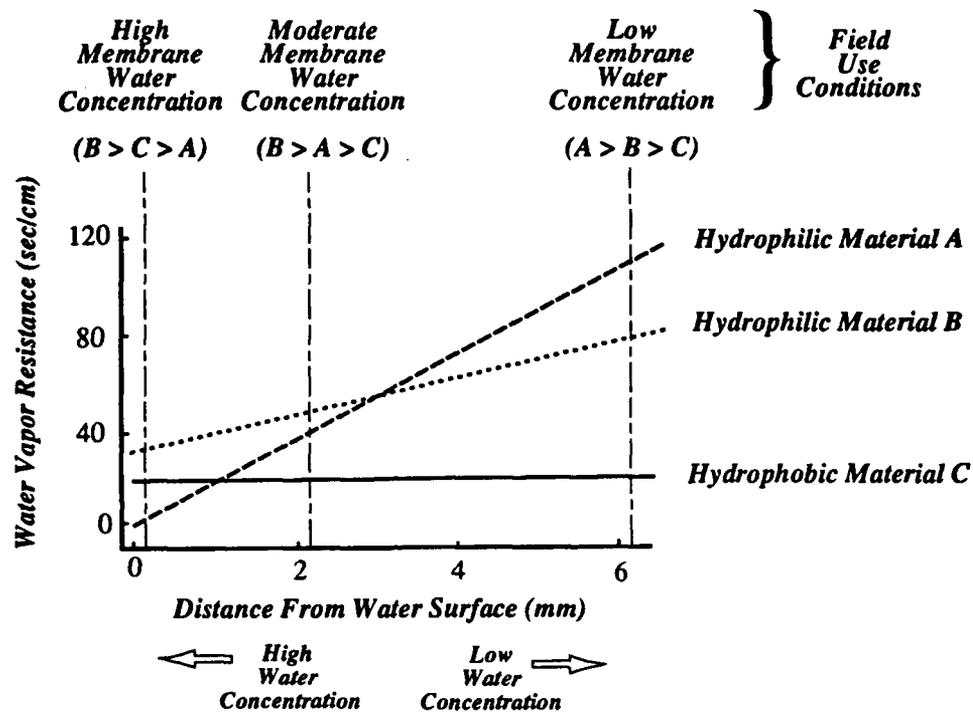


Figure 15. Variation of Water Vapor Resistance with Average Water Concentration in Membrane.

It's clear that the choice of test conditions can greatly influence the rankings of candidate materials. At the extreme of high membrane water concentration, hydrophilic membrane A has the lowest water vapor resistance, and would appear to have the best water vapor transport properties. At the other extreme of low membrane water concentration, hydrophobic membrane C appears to be much better than the other materials, and hydrophilic membrane A is clearly the worst performing material. At moderate membrane water concentration levels, which are more representative of conditions which might be found in a clothing system, one could pick test conditions such that either membrane A or C is rated superior, and the relative ranking of membranes A and B can reverse depending on which test conditions are used.

In the case illustrated by Figure 15, it would be prudent to evaluate and rank the water vapor permeability of candidate membrane laminates on a device such as a guarded sweating hot plate, which more accurately simulates the heat and mass transfer conditions present for the skin/clothing system. The use of ASTM E96-80, Procedures B and BW, to evaluate and rank semipermeable membrane laminates against each other would be justified only if one material consistently exhibits higher water vapor permeability in both Procedure B and Procedure BW.

Comments on Multilayer Clothing Systems Incorporating Hydrophilic Membranes

The water vapor transport behavior of hydrophilic membrane laminates is highly dependent on the water concentration in the membrane. This means the effectiveness of the membrane is influenced by both the microclimate underneath clothing, and the environment outside the clothing system. The extremes in microclimate underneath the clothing are: 1) a low human work rate where little sweat is being produced and the humidity is about the same as the outside environment, and 2) a high human work rate, where a large amount of sweat is being produced and the water vapor pressure underneath the clothing approaches saturation vapor pressure. The extremes of the outside environment are simply low or high ambient humidity. The temperature differences between the skin and the outside air, and condensation/accumulation of sweat in clothing layers are complicating factors that will not be addressed here.

The intrinsic water vapor resistance of permeable materials and hydrophobic membrane laminates would not be affected much by the ambient humidity or human sweating rate. In contrast, the intrinsic water vapor resistance of monolithic hydrophilic membrane laminates would be affected by both ambient humidity and the human sweating rate. This difference between the two classes of materials is illustrated schematically in Figure 16.

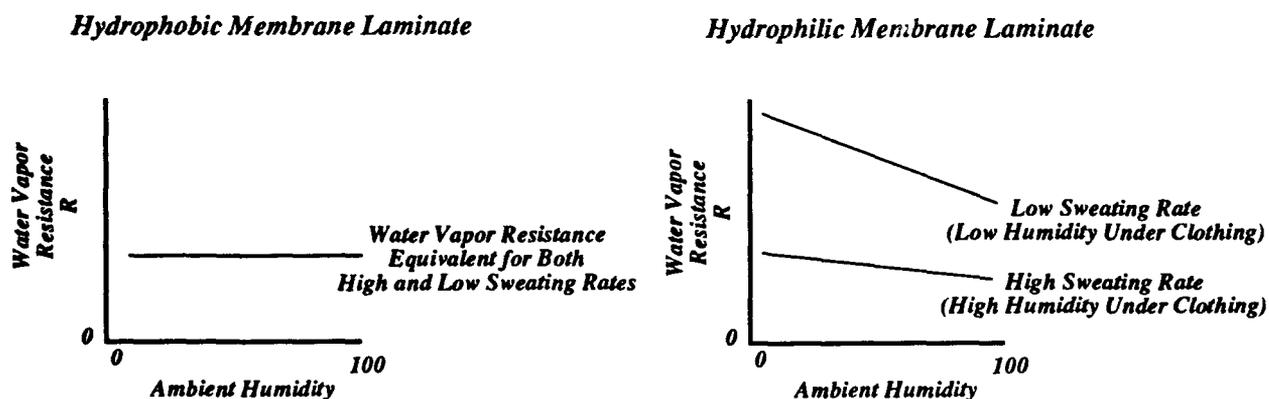
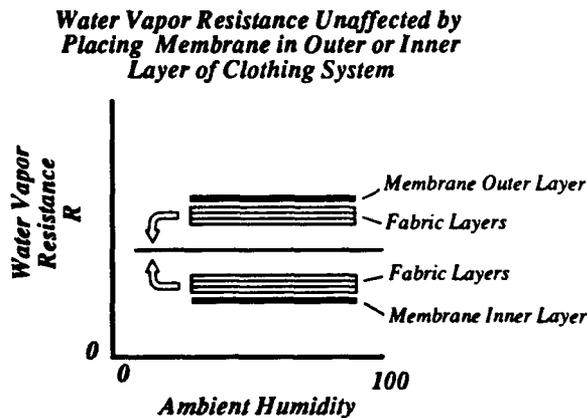


Figure 16. Water Vapor Resistance of Hydrophilic Membrane Laminates Depends on Ambient Humidity and Human Sweating Rate

The main point of Figure 16 is that the water vapor transport behavior of hydrophilic semipermeable membranes is greatly influenced by the amount of water dissolved in them. The moisture vapor transmission rate of hydrophilic membranes "adapts" to use conditions. That is, the intrinsic water vapor resistance of these materials decreases under precisely those conditions where increased water vapor transport is desired: high human sweating rates and/or high ambient humidity.

The water vapor resistance of a multilayer clothing system may also be altered by changing the configuration of the layers of clothing. If a hydrophilic membrane laminate is incorporated in the inner layer as opposed to the outer layer of a clothing system, the equilibrium water concentration of the hydrophilic layer will again be dependent on the relative humidity it is exposed to. This is illustrated in Figure 17, where it is assumed that the microclimate next to the skin is saturated due to sweat production at high human work rates.

Hydrophobic Membrane Laminate



Hydrophilic Membrane Laminate

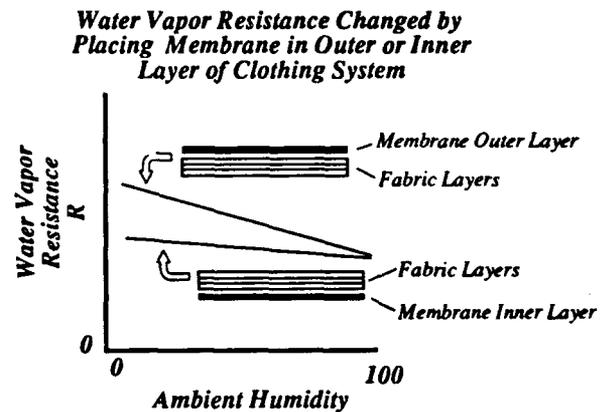


Figure 17. Placement of Hydrophilic Membrane Laminate Affects Water Vapor Resistance of Multilayer Clothing Systems (High Human Sweating Rate Assumed).

If the hydrophilic polymer layer is next to the skin, water vapor is concentrated within the clothing, and the membrane has a higher equilibrium water content than if it was the outermost layer and exposed to a low ambient humidity. At conditions of high humidity, the relative difference between the performance of the hydrophilic membranes incorporated into the outermost layer versus the innermost layer becomes much less important.

The above discussion ignores many important factors, such as the role of temperature differences within the clothing system, and the condensation/accumulation of sweat in various clothing layers. A numerical model developed by Farnworth⁴⁰ was successful in modeling both heat and water vapor transfer through multilayer clothing systems while taking into account all the complicating factors just mentioned. Although the model did not incorporate concentration-dependent water vapor resistances, the system of equations is amenable to incorporating such a modification. The importance of factors such as configuration to the performance of a multilayer clothing system incorporating hydrophilic membrane laminates could be assessed with Farnworth's modified model.

5. Conclusions and Recommendations

Conclusions

- Guarded sweating hot plate and ASTM E96-80, Procedure B, water vapor permeability test methods correlate quite well for a wide variety of woven and nonwoven permeable fabrics, and hydrophobic microporous semipermeable membrane laminates.
- Hydrophilic monolithic semipermeable membrane laminates show no correlation between the sweating guarded hot plate and the ASTM E96-80, Procedure B, upright cup test. This is due to the concentration-dependent water vapor resistance of the hydrophilic polymer layer, and the fact that the two types of tests result in different equilibrium water concentrations in test samples.

Recommendations

- Water vapor permeability screening tests on hydrophilic membranes and laminates should be done under conditions which approximate the actual use conditions. The ranking of various materials will change dramatically according to the water concentration in the hydrophilic polymer layer.
- ASTM E96-80, Procedure B and Procedure BW, may be used together to rank the water vapor permeability of candidate materials only if one material shows better water vapor transport properties in both test methods. If the rankings change between Procedure B and BW, then some other method, such as the sweating guarded hot plate, should be used to rank the materials.
- Materials with ASTM E96-80, Procedure B, *MVTR* values greater than $1200 \text{ g}\cdot\text{m}^{-2}/24 \text{ hours}$ are influenced by air penetration through the fabric. Unless the fabric will actually be used as a single layer, it is better practice to perform comparison tests with other materials using a cover fabric with low water vapor resistance.
- Farnworth's numerical model⁴⁰ of heat and moisture transfer through multilayer clothing systems should be adapted to incorporate concentration-dependent water vapor resistances of monolithic hydrophilic polymer layers. The optimum placement of the hydrophilic membrane could be determined for a variety of human work rates and external environmental conditions.

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This document reports research undertaken at the US Army Natick Research, Development and Engineering Center and has been assigned No. NATICK/TR-721046 in the series of reports approved for publication.

APPENDIX A

Intrinsic Water Vapor Resistance Units

A system of intrinsic thermal resistance and intrinsic water vapor resistance units is used by the Hohenstein Institute in Boennigheim, Germany. These units are incorporated into the draft DIN Standard 54-101²⁸, and also in NATO guidelines²⁹ for determining the heat transfer properties of clothing. This system of units can be easily converted back to i_m and clo units as shown at the end of this section.

$$\text{Thermal Resistance, } R_{ct} = \frac{(T_{plate} - T_{air})(A)}{Q} - R_{ct0} \quad (\text{A.1})$$

- R_{ct0} = bare plate thermal resistance of boundary air layer ($\text{m}^2\text{-}^\circ\text{K}/\text{watt}$)
- A = Surface area of guarded plate measurement area (m^2)
- T_{plate} = Temperature of the plate surface ($^\circ\text{K}$)
- T_{air} = Temperature of the ambient air ($^\circ\text{K}$)
- Q = Power required to maintain a constant plate surface temperature (watts)

$$\text{Water Vapor Resistance, } R_{et} = \frac{(p_s - \phi p_a)(A)}{Q} - R_{et0} \quad (\text{A.2})$$

- R_{et0} = bare plate water vapor resistance of boundary air layer ($\text{m}^2\text{-mbar}/\text{watt}$)
- A = Surface area of guarded plate measurement area (m^2)
- T_{plate} = Temperature of the plate surface ($^\circ\text{K}$)
- T_{air} = Temperature of the ambient air ($^\circ\text{K}$)
- 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_{m_i} is given by:

$$i_{m_i} = S_1 \frac{R_{ct}}{R_{et}} \quad (\text{A.3})$$

where S_1 is $0.6 \text{ mbar}/^\circ\text{K}$ (or $0.45 \text{ mmHg}/^\circ\text{C}$), and is equal to $1/S$ (S defined previously as $2.2 \text{ }^\circ\text{C}/\text{mmHg}$).

The conversion factor used to convert DIN 54-101 units to clo and i_m units is shown below:

$$\begin{aligned} \text{Bare plate thermal resistance } R_o &= (6.46)R_{clo} \\ \text{Total thermal resistance } R_{total} &= (6.46)(R_{clo} + R_{ct}) \\ \text{Intrinsic thermal resistance } R_i &= (6.46)R_{ct} \end{aligned}$$

where R_o , R_{total} , and R_i are in clo units; R_{clo} and R_{ct} are in $m^2 \cdot ^\circ K / \text{watt}$.

The water vapor permeability index i_m is found from:

$$i_m = S_1 \frac{(R_{ct} + R_{ct0})}{(R_{et} + R_{et0})} \quad (\text{A.4})$$

The evaporative resistance R_{et} may be obtained from i_m and R_{total} (clo) values from:

$$R_{et} = S_1 \left(\frac{R_{ct} + R_{ct0}}{i_m} \right) - R_{et0} = \frac{S_1}{6.46} \left\{ \frac{1}{(i_m / R_{tot})} - \frac{1}{(i_{m0} / R_o)} \right\} \quad (\text{A.5})$$

where i_{m0} is bare plate i_m value.

APPENDIX B

ASTM E96-80, Procedure B Measurements

**Table B-1. Permeable Materials
(Upright Cup Data)**

Sample #	MVTR (g·m ² /24 h)	Equivalent Air Resistance d_{eq} (cm of still air)	Intrinsic Fabric Resistance R_f (s/cm)
1	987	0.430	1.68
2	988	0.428	1.67
3	1216	-0.008	-0.03
4	958	0.501	1.96
5	1101	0.189	0.74
6	980	0.447	1.75
7	683	1.467	5.73
8	745	1.187	4.64
9	701	1.381	5.39
10	761	1.122	4.38

Values in table are averaged over four samples.

**Table B-2. Hydrophobic Membrane Laminates
(Upright Cup Data)**

Sample #	MVTR (g·m ² /24 h)	Equivalent Air Resistance d_{eq} (cm of still air)	Intrinsic Fabric Resistance R_f (s/cm)
11	1035	0.322	1.26
12	824	0.891	3.48
13	879	0.717	2.80
14	790	1.01	3.95
15	740	1.21	4.72
16	789	1.02	3.97
17	872	0.738	2.88
18	895	0.670	2.62
19	809	0.943	3.68

Values in table are averaged over four samples.

**Table B-3. Hydrophilic Membrane Laminates
(Upright Cup Data)**

Sample #	MVTR (g·m ⁻² /24 h)	Equivalent Air Resistance d_{eq} (cm of still air)	Intrinsic Fabric Resistance R_f (s/cm)
20	675	1.51	5.88
21	623	1.79	7.00
22	461	3.09	12.07
23	517	2.55	9.96
24	531	2.43	9.50
25	567	2.16	8.42
26	602	1.92	7.50
27	673	1.52	5.93

Values in table are averaged over four samples.

**Table B-4. Impermeable Material
(Upright Cup Data)**

Sample #	MVTR (g·m ⁻² /24 h)	Equivalent Air Resistance d_{eq} (cm of still air)	Intrinsic Fabric Resistance R_f (s/cm)
28	1	2298	8976

APPENDIX C

Sweating Guarded Hot Plate Measurements

**Table C-1. Permeable Materials
(Sweating Hot Plate Data)**

Bare Plate $R_{ci0} = 0.0542 \text{ m}^2\cdot\text{K}/\text{watt}$
 Bare Plate $R_{ct0} = 0.0325 \text{ to } 0.0328 \text{ m}^2\cdot\text{mbar}/\text{watt}$

Sample #	Intrinsic C _{lo} (R _i)	Total C _{lo} (R _{total})	I _m	I _m /C _{lo} (I _m /R _{total})	R _{ci} (m ² ·K/watt)	R _{ct} (m ² ·mbar/watt)	I _{mt}	MVTR _{plac} (g·m ⁻² /24 h)
1	0.15	0.50	0.61	1.22	0.0232	0.0436	0.32	8303
2	0.18	0.53	0.72	1.36	0.0279	0.0359	0.47	9256
3	0.21	0.56	0.65	1.16	0.0325	0.0475	0.41	7894
4	0.41	0.76	0.54	0.71	0.0635	0.0982	0.39	4832
5	0.27	0.62	0.48	0.78	0.0418	0.0875	0.29	5308
6	0.27	0.62	0.69	1.11	0.0418	0.0509	0.49	7554
7	0.53	0.88	0.52	0.59	0.0820	0.1247	0.39	4015
8	0.39	0.74	0.48	0.64	0.0604	0.1107	0.33	4355
9	0.54	0.89	0.49	0.55	0.0836	0.1362	0.37	3743
10	0.39	0.74	0.46	0.62	0.0604	0.1169	0.31	4219

**Table C-2. Hydrophobic Membrane Laminates
(Sweating Hot Plate Data)**

Bare Plate $R_{co} = 0.0542 \text{ m}^2\cdot\text{K}/\text{watt}$

Bare Plate $R_{ci} = 0.0325 \text{ to } 0.0328 \text{ m}^2\cdot\text{mbar}/\text{watt}$

Sample #	Intrinsic C _{lo} (R_i)	Total C _{lo} (R_{total})	I_m	I_m/C_{lo} (I_m/R_{total})	R_{ci} ($\text{m}^2\cdot\text{K}/\text{watt}$)	R_{ci} ($\text{m}^2\cdot\text{mbar}/\text{watt}$)	I_{m1}	MVTR _{plate} ($\text{g}\cdot\text{m}^{-2}/24 \text{ h}$)
11	0.21	0.56	0.60	1.06	0.0325	0.0538	0.36	7214
12	0.25	0.60	0.38	0.63	0.0387	0.1138	0.20	4288
13	0.12	0.47	0.39	0.83	0.0186	0.0791	0.14	5649
14	0.15	0.50	0.32	0.67	0.0232	0.1123	0.12	4560
15	0.17	0.52	0.27	0.52	0.0263	0.1460	0.11	3539
16	0.19	0.54	0.36	0.67	0.0294	0.1065	0.17	4560
17	0.13	0.48	0.28	0.59	0.0201	0.1264	0.10	4015
18	0.13	0.48	0.31	0.64	0.0201	0.1110	0.11	4356
19	0.13	0.48	0.33	0.69	0.0201	0.1023	0.12	4696

**Table C-3. Hydrophilic Membrane Laminates
(Sweating Hot Plate Data)**

Bare Plate $R_{eq} = 0.0542 \text{ m}^2\cdot\text{K}/\text{watt}$
 Bare Plate $R_{eq} = 0.0325 \text{ to } 0.0328 \text{ m}^2\cdot\text{mbar}/\text{watt}$

Sample #	Intrinsic Clo (R_1)	Total Clo (R_{total})	I_m	I_m/Clo (I_m/R_{total})	R_{ct} ($\text{m}^2\cdot\text{K}/\text{watt}$)	R_{ct} ($\text{m}^2\cdot\text{mbar}/\text{watt}$)	I_{m1}	MVTR _{plate} ($\text{g}\cdot\text{m}^{-2}/24 \text{ h}$)
20	0.12	0.47	0.57	1.22	0.0186	0.0437	0.25	8303
21	0.14	0.49	0.28	0.58	0.0217	0.1297	0.10	3947
22	0.16	0.51	0.29	0.56	0.0248	0.1305	0.11	3811
23	0.15	0.50	0.49	0.98	0.0232	0.0619	0.22	6670
24	0.17	0.52	0.46	0.88	0.0263	0.0722	0.22	5989
25	0.21	0.56	0.31	0.56	0.0325	0.1349	0.14	3811
26	0.15	0.50	0.41	0.83	0.0232	0.0804	0.17	5648
27	0.16	0.51	0.59	1.16	0.0248	0.0474	0.31	7894

Table C-4. Impermeable Material

Sample #	Intrinsic Clo (R_1)	Total Clo (R_{total})	I_m	I_m/Clo (I_m/R_{total})	R_{ct} ($\text{m}^2\cdot\text{K}/\text{watt}$)	R_{ct} ($\text{m}^2\cdot\text{mbar}/\text{watt}$)	I_{m1}	MVTR _{plate} ($\text{g}\cdot\text{m}^{-2}/24 \text{ h}$)
28	0.08	0.43	0.02	0.05	0.0124	1.9644	0.00	136