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MODELING COMPARATIVE THERMAL PERFORMANCE OF LIGHTWEIGHT FABRICS USING A COMPUTATIONAL DESIGN TOOL

by
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May 2014 – July 2015

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14. ABSTRACT

Lightweight fabrics are of current interest for new military uniforms under development for hot and humid conditions. Tropical environments present a unique set of challenges such as the need to minimize heat stress, while still providing protection from disease-carrying organisms that are often pervasive in these environments. Thermal comfort is particularly important and will be highly dependent on the ability of the fabric to maximize evaporative cooling and heat exchange with the environment. In the work presented in this report, a computational design tool was used to compare the relative performance of a set of fabrics that would potentially be used in a new lightweight military uniform. These predicted coefficients can be used by themselves or input into human heat balance equations to predict relative performance differences under specific environmental conditions of wind speed, relative humidity, and environmental temperature.

15. SUBJECT TERMS

FABRICS	MODELING	DESIGN TOOLS	HEAT TRANSFER	RELATIVE HUMIDITY
TEXTILES	EQUATIONS	LIGHTWEIGHT	WIND VELOCITY	HIGH TEMPERATURE
COMFORT	WIND SPEED	PERMEABILITY	HEAT EXCHANGE	PROTECTIVE CLOTHING
HUMIDITY	BREATHABLE	TEMPERATURE	DISEASE VECTORS	EVAPORATIVE COOLING
MANIKINS	COEFFICIENTS	HEAT BALANCE	TROPICAL REGIONS	TEST AND EVALUATION
UNIFORMS	HOT REGIONS	ENVIRONMENTS	THERMAL COMFORT	HEAT STRESS(PHYSIOLOGY)
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Preface

This report documents work performed by the Warfighter Directorate of the U.S. Army Natick Soldier Research, Development and Engineering Center (NSRDEC) during the period May 2014 through July 2015. The work was supported by PE 0602786A Warfighter Technology E01 Warfighter Technology Initiatives and by PE 0602786A / Warfighter Technology H98 / Clothing & Equipment Tech. The work presented here was part of a larger project in 2014/2015 to investigate the performance of novel textile and fiber-based technologies to provide protection against multiple environmental threats to Soldiers and Small Units.

MODELING COMPARATIVE THERMAL PERFORMANCE OF LIGHTWEIGHT FABRICS USING A COMPUTATIONAL DESIGN TOOL

1. Introduction

Work for this report was performed from May 2014 through July 2015 by the Warfighter Directorate of the U.S. Army Natick Soldier research, Development and Engineering Center (NSRDEC).

Lightweight fabrics are of current interest for new military uniforms under development for hot and humid conditions. Tropical environments present a unique set of challenges, such as the need to minimize heat stress while still providing protection from disease-carrying organisms that are often pervasive in these environments. Thermal comfort is particularly important and will be highly dependent on the ability of the fabric to maximize evaporative cooling and heat exchange with the environment. In the work presented in this report, a computational design tool was used to compare the relative performance of a set of fabrics that would potentially be used in a new lightweight military uniform.

2. Materials

Table 1 lists the 7 fabrics that were evaluated in this study, which are a subset of 18 fabrics that are part of a larger project aimed at evaluating the relevant performance properties for a new tropical military uniform [1].

Table 1. Test Fabrics.

Fabric ID	Fabric Notes
Micro-Cotton	100% Cotton
Airplane Cotton	100% Cotton
ACU NyCo (Army Combat Uniform Nylon-Cotton)	50% Nylon - 50% Cotton Ripstop
MCCUU NyCo LW (Marine Corps Combat Utility Uniform, Lightweight)	50% Nylon - 50% Cotton Twill
FR ACU Type III (Fire Resistant Army Combat Uniform)	FR Blend (Defender M) Ripstop 65% FR Rayon 25% P-Aramid 10% Nylon
FR ACU Type IV (Fire Resistant Army Combat Uniform)	FR Blend (Defender M) Twill 65% FR Rayon 25% P-Aramid 10% Nylon
Sigma Versatech	FR Blend Ripstop 45% M-Aramid 32%FR Rayon 17% Nylon

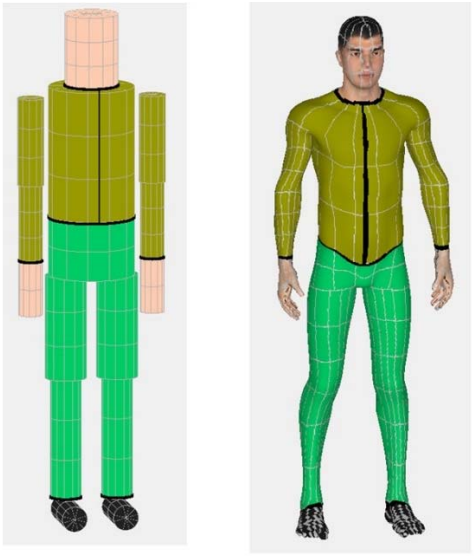
3. Methods

3.1 Fabric Transport Properties: Water Vapor Diffusion, Air Permeability, Thermal Resistance

For thermal comfort, the most important factors are properties related to water vapor transport (sweat evaporation), thermal transport (conduction and convection of heat), and air flow through the fabric (air permeability or air flow resistance). Fabric transport properties were measured on small fabric samples using the sweating guarded hot plate method for thermal resistance [2] and the dynamic moisture permeation cell method for water vapor transport and air flow resistance [3]. Further details on these test methods are contained in Appendix A.

3.2 Computational Model – IP SPM

These fabric transport properties were input into a computational design tool developed by Creare, Inc., for the U.S. military, which provides a physics-based computational framework for iterative modification and assessment of protective clothing systems [4]. Creare's Individual Protection System Performance Model (IP SPM) (Appendix B) is built upon a foundation of advanced computational fluid dynamic and experimental results, but the software itself is purposefully simplified to allow non-expert users to modify clothing designs and assess the consequences of various clothing aspects (such as fit, closures, interfaces, material properties, layering, etc.) on comfort and protection. The IP SPM model treats the clothed human body as an assemblage of fabric-covered cylinders, although the graphical user interface maps clothing layers onto a more anatomically correct human figure, as shown in Figure 1. Computational models that include more detailed human and clothing geometry are possible [5], and in fact these geometries are used as some of the guides for the IP SPM software. But, too much detail has been found to add an unneeded level of complexity for a user-friendly design tool, especially for non-expert users. Previous work with this computational tool has shown good correlation of computational predictions with experimental thermal manikin measurements for a variety of clothing systems [6].



Primary Clothing Properties (steady state):
Air Flow Resistance
Water Vapor Diffusion Resistance
Thermal Resistance

Clothing System:
Layers, Gaps, Vents,
Closures, Patches

Environment:
Temperature, Humidity
Wind Speed, Thermal Radiation

Body Geometry:
Body Segment Size/Diameter
Body Surface Temperature

Cylinders Mapped to More Realistic Clothed Image

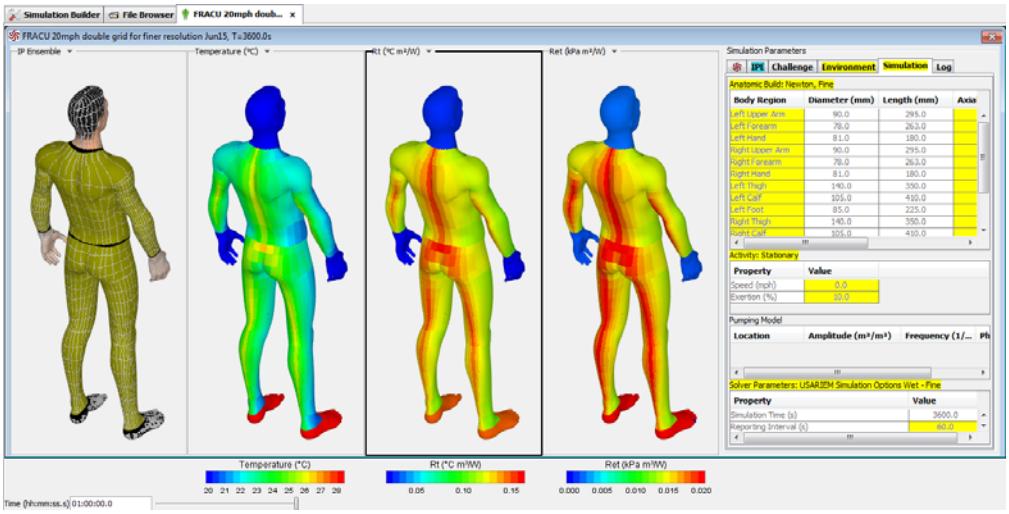


Figure 1. Typical IP SPM Simulation.

The Creare IP SPM can be configured to simulate a thermal manikin, which is an important tool in clothing comfort research. Figure 2 shows baseline comparison results for the IP SPM thermal manikin calculated overall heat transfer coefficients as compared to some empirical correlations obtained with humans [7] and thermal manikins [8], as well as computational and analytical results from heated cylinders [9].

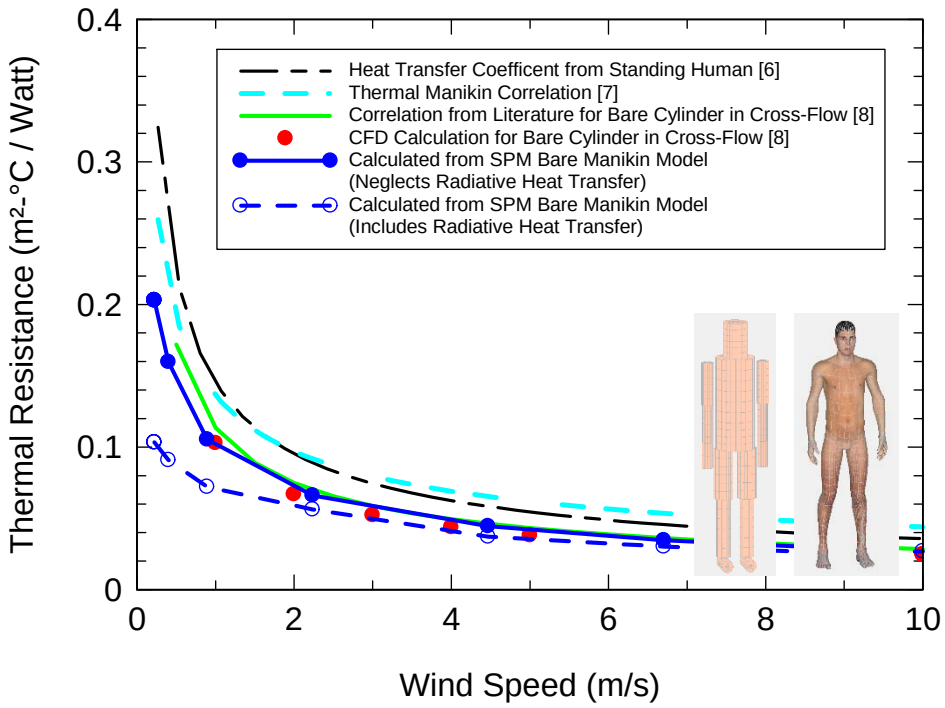
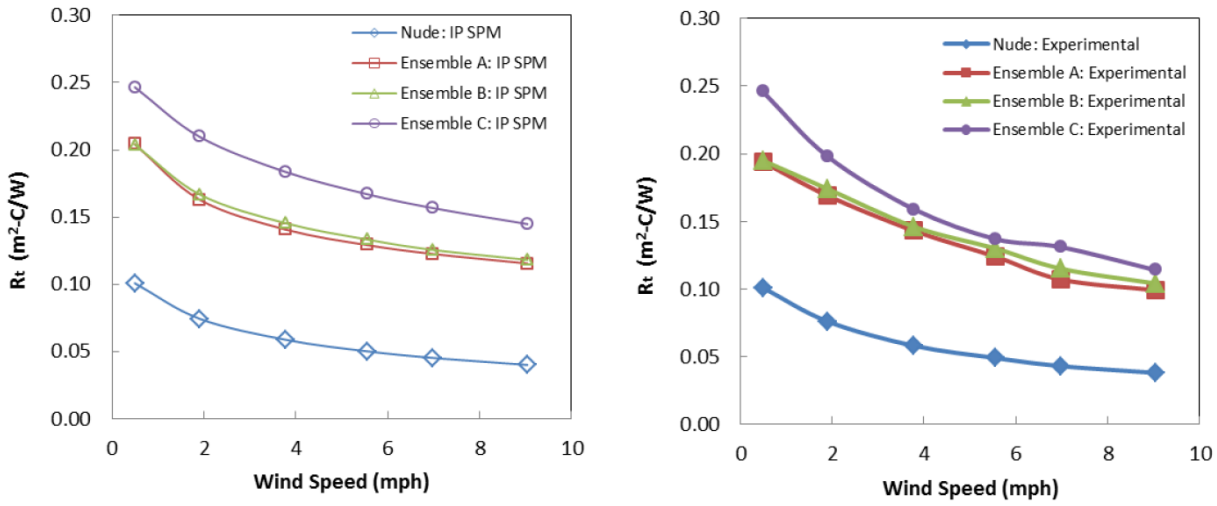


Figure 2. Overall Heat Transfer Coefficient of IP SPM Thermal Manikin as a Function of Wind Speed.

Figure 2 shows an under prediction of bare manikin values at low wind speeds when radiative heat transfer is included in the IP SPM model; when this is removed from the calculation (h_{rad} of 4.5 W/m²-°C), the IP SPM results show good agreement with the convective-only heat transfer calculations from reference [8] shown in Figure 2.

IP SPM predictions can be compared to experimental thermal manikin results, as reported previously [6]. Inputs to the IP SPM model require clothing thermal resistance, water vapor diffusion resistance, and air flow resistance for the fabric, and some information on the fit (space between the fabric and the body surface), tightness of the closures and seams, and the extent of coverage of the fabric over different sections of the body. Figure 3 shows a comparison of IP SPM predictions to experimental results obtained by a thermal manikin [10, 11] for both the bare (nude) condition and for three separate clothing ensembles on the manikin.



(a) IP SPM (b) Thermal Manikin

Figure 3. Comparison of Thermal Insulation for the Nude Manikin and Three Clothing Ensembles: (a) IP SPM Model Results versus (b) Experimental Thermal Manikin Results.

As shown in Figure 3, the performance rankings between the ensembles were correctly replicated by the IP SPM predictions, for both the overall thermal resistance (shown in Figure 3) and evaporative resistances (not shown). This result is important because it indicates that in situations where the exact experimental configurations are not known or defined, the IP SPM can still be used to determine relative garment rankings for thermal performance using nominal configuration values (e.g., for garment fit or different fabrics used for the same garment).

4. Results and Discussion

4.1 Experimental Measurement of Fabric Properties

Fabric properties, as measured by the Dynamic Moisture Permeation Cell (DMPC) and the Guarded Hot Plate (GHP), are shown in Table 2. Also given in the last column are the parameters required by the computational model, as described in Appendix C. The IP SPM assumes a given fabric thickness (nominally 0.124 cm), and the properties input into the model require some unit conversion so that that they may be input into the simulation panels.

Table 2. Fabric Properties Measured by DMPC and GHP.

Thermal Resistance (GHP)

Fabric ID	Thermal Resistance (Rc) m^2-°C/Watt Fabric + Plate	Thermal Resistance m^2-°C/Watt Bare Plate	Thermal Resistance m^2-°C/Watt Fabric Only	**IP SPM Model Input** **Thermal Conductivity** W/m-°C
Micro-Cotton	0.0725	0.0578	0.0147	0.0799
Airplane Cotton	0.0771	0.0578	0.0193	0.0645
ACU NyCo (Army Combat Uniform Nylon-Cotton)	0.0753	0.0578	0.0175	0.0799
MCCUU NyCo LW (Marine Corps Combat Utility Uniform, Lightweight)	0.0715	0.0580	0.0135	0.0922
FR ACU Type III (Fire Resistant Army Combat Uniform)	0.0821	0.0578	0.0243	0.0512
FR ACU Type IV (Fire Resistant Army Combat Uniform)	0.0787	0.0578	0.0209	0.0596
Sigma Versatech	0.0749	0.0578	0.0171	0.0728

Water Vapor Diffusion Resistance (DMPC)

Fabric ID	Water Vapor Diffusion Resistance s/m Fabric + Boundary Layer	Water Vapor Diffusion Resistance s/m Boundary Layer Only (ePTFE Membrane)	Water Vapor Diffusion Resistance s/m Fabric Only	**Water Diffusivity** m^2/s
Micro-Cotton	148	116	32	3.83E-05
Airplane Cotton	158	116	42	2.96E-05
ACU NyCo (Army Combat Uniform Nylon-Cotton)	207	116	91	1.37E-05
MCCUU NyCo LW (Marine Corps Combat Utility Uniform, Lightweight)	176	116	60	2.08E-05
FR ACU Type III (Fire Resistant Army Combat Uniform)	203	116	87	1.43E-05
FR ACU Type IV (Fire Resistant Army Combat Uniform)	211	116	95	1.31E-05
Sigma Versatech	175	116	59	2.10E-05

Air Flow Resistance (DMPC)

Fabric ID	Air Flow Resistance 1/m	Air Permeability $ft^3/min/ft^2$	**Air Flow Resistance** 1/m
Micro-Cotton	2.04E+08	7	2.04E+08
Airplane Cotton	2.58E+07	53	2.58E+07
ACU NyCo (Army Combat Uniform Nylon-Cotton)	2.13E+08	6	2.13E+08
MCCUU NyCo LW (Marine Corps Combat Utility Uniform, Lightweight)	6.67E+07	21	6.67E+07
FR ACU Type III (Fire Resistant Army Combat Uniform)	3.81E+07	36	3.81E+07
FR ACU Type IV (Fire Resistant Army Combat Uniform)	2.79E+07	49	2.79E+07
Sigma Versatech	2.36E+08	6	2.36E+08

4.2 Computational Results

Typical computational predictions of the overall heat and mass transfer coefficients (equivalent to experimental clothed sweating thermal manikin measurements) are shown in Figure 4 for the fabrics listed in Table 2.

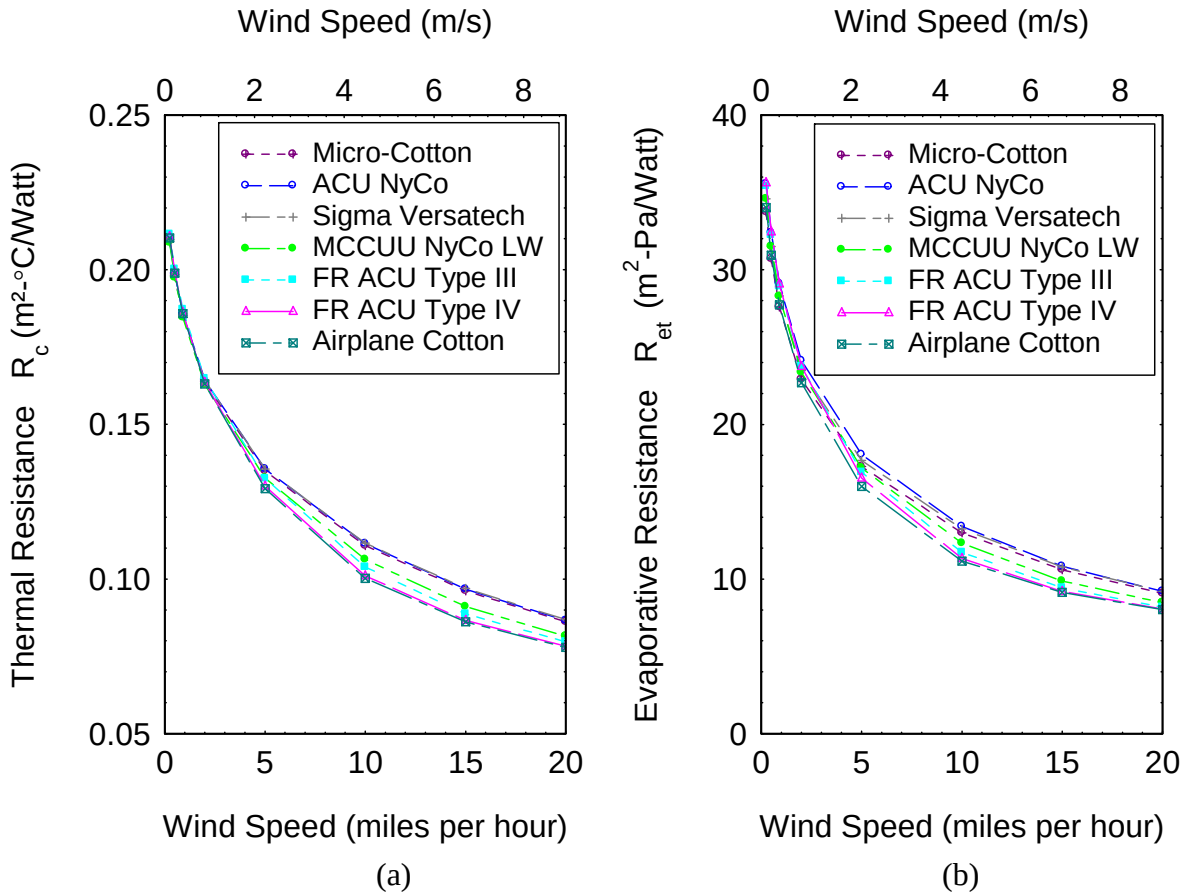


Figure 4. Computational Predictions of Equivalent Sweating Thermal Manikin Measurements: (a) thermal resistance (R_c) and (b) evaporative resistance (R_{et}) for simulated clothing systems composed of lightweight fabrics.

4.3 Review of Clothing Heat Transfer Coefficients

Heat transfer through clothing is often broken down into dry heat transfer (conduction, convection, and radiation) and evaporative heat transfer (diffusion and convection of evaporated sweat vapor). Typical units to characterize clothing dry heat transfer are thermal resistance R_c (m²-°C/Watt) and the alternate thermal resistance unit of clo. Typical units for evaporative heat transfer are evaporative resistance R_{et} (m²-Pa/Watt), the equivalent parameter i_m/clo, and the related water vapor transfer rate, WVTR (g/m²-day). These properties may all be dependent to some extent on the measurement methods used -- material properties related to air permeability, liquid sweat wicking, etc., may be lumped together into overall measurements made using system tests such as sweating thermal manikins.

Conventional testing methods for obtaining thermal properties for clothing heat balance include the sweating guarded hot plate, water-filled cup tests, and various permeation cells. All give equivalent values and can be converted if testing conditions are known. I_m (permeability index) 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 thermal manikin or sweating guarded hot plate becomes great enough to minimize the contribution of radiative heat transfer. In heat balance equations, the thermal resistance is divided out of the i_m index to give the variable related to water vapor permeability (i_m /clo, R_{et}, MVTR, etc.). The effects of wind speed and measurement bias can be subtracted off to give "intrinsic" values for the materials that are closer to true material properties. For clothing system testing (i_m, clo), all values depend on wind speed, fit, and air permeability [12] (commonly included by testing thermal manikins at three different wind speeds).

As mentioned previously, total heat transfer is equal to dry heat transfer plus evaporative heat transfer. 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:

$$E_{dry}(watts\ /\ m^2) = \left(\frac{6.45}{clo}\right)(\Delta T) \qquad (1)$$

$$E_{evap}(watts\ /\ m^2) = i_m\left(\frac{6.45}{clo}\right)S(\Delta p) \qquad (2)$$

$$\text{Total Heat Transfer (watts/m}^2) = \left(\frac{6.45}{clo}\right)(\Delta T) + 14.2\left(\frac{i_m}{clo}\right)(\Delta p) \qquad (3)$$

ΔT = temperature difference, °C
S = Lewis Relation (2.2 °C/mmHg)
Δp = vapor pressure difference, mmHg
clo = R_c in clo units

It is important to note that the value for i_m/clo is inversely equivalent to evaporative resistance R_{et} (m^2-Pa/Watt) as defined in an alternate system of units, and can also be converted directly into water vapor flux values (g/m^2-day) [2].

4.4 Using Modeling Results in Clothed Human Heat Balance Comparisons - Thermal Physiology Implications

The conventional heat balance equation, which describes energy flows between the clothed human body and the environment, is as follows [13]:

$$M + W + R + C + E_D + E_{re} + E_{sw} + S = 0 \quad (4)$$

M = metabolic rate (internal energy produced by food oxidation)
W = the physical work
R = the net radiant balance of the body
C = the heat flow due to conduction and convection
E_D = the latent heat flow to evaporate water through skin (perspiration)
E_{re} = heat flows for respiration (air heating and humidifying)
E_{sw} = heat flow due to sweat evaporation
S = heat flow accumulated in body.

For thermal balance, the heat generated due to metabolism and exercise is equal to the heat dissipated through clothing. Numerical values for heat generated due to metabolism and exercise (watts per unit body surface area) are available in standard tables [14].

The heat lost through clothing can be related to the calculated heat and mass transfer coefficients for the fabric covered cylinders for the fabrics from Table 1.

$$\text{Heat lost through clothing} = (\Delta T / R_c) + (\Delta p_v / R_{et}) \quad (5)$$

ΔT = temperature difference between skin and environment (°C)
R_c = thermal resistance (m²-°C/Watt)
Δp_v = vapor pressure difference between skin and environment (Pa)
R_{et} = water vapor diffusion resistance (m²-Pa/Watt)

The heat loss rate from a clothed human can be calculated for different wind speeds using the R_{et} and R_c values from Figure 2 for specific environmental conditions of wind speed, temperature, and relative humidity. A typical calculation can be made for the situation where the heat loss rate is chosen to be at the maximum to avoid "excess" sweating. Because the total heat transfer and mass transfer coefficients are available as a function of wind speed for the fabrics, the maximum activity level to maintain thermal balance can also be calculated over the range of wind speeds from 0 to 20 mph [15]. These predictions, such as that shown in Figure 5, allow a more direct comparison of the performance properties of the fabrics in specific environmental conditions (such as hot-dry or hot-humid) than would be available from just looking at measured fabric properties, such as those in Table 2.

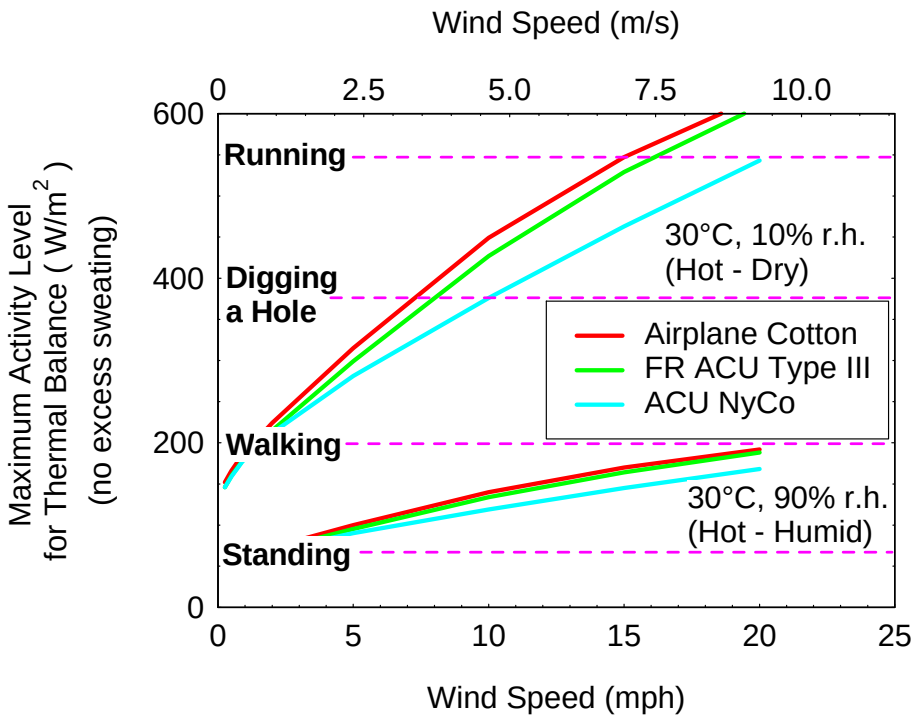


Figure 5. Maximum Activity Level to Avoid Sweating for Various Wind Speeds and Activity Levels for Three Lightweight Fabrics.

Heat balance equations using the computed heat and mass transfer coefficients also provide the relative proportions of dry heat transfer and evaporative heat transfer for each type of clothing. Figure 6 shows that the dry heat loss due to conduction and convection is less than that due to evaporated sweat for the environmental conditions of 30 °C, 90% r.h., and 5 mph wind speed.

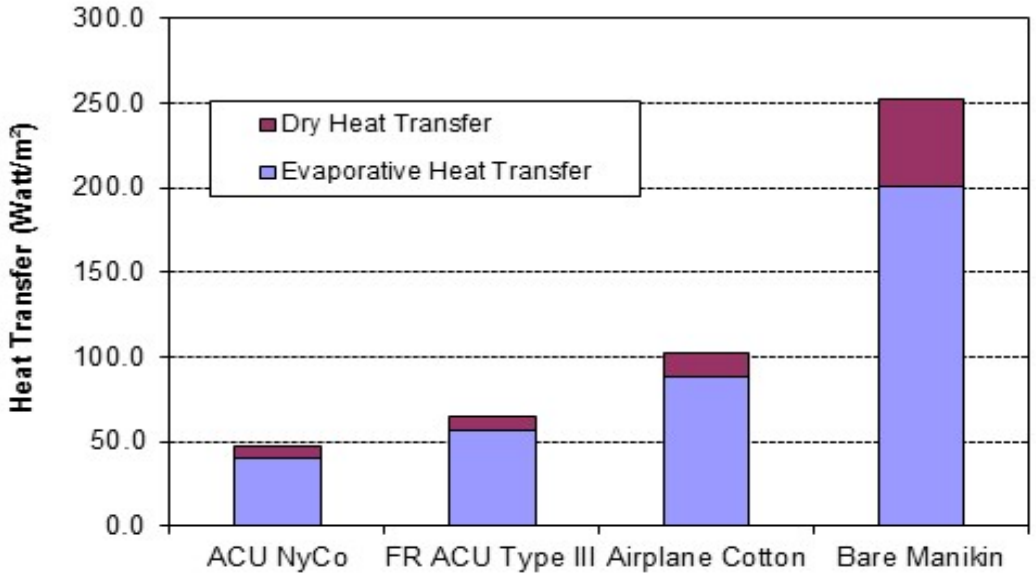


Figure 6. Example of Relative Contributions of Dry Heat Transfer and Evaporative Heat Transfer for One Condition of Environmental Temperature, Humidity, and Wind Speed (5 mph, 30°C, 90% r.h.).

5. Conclusions

A computational design tool, developed by Creare, Inc. for the U.S. military, allows a simple clothing system to be placed on a human body form to predict heat and mass transfer coefficients that are equivalent to what would be predicted from a sweating thermal manikin. These predicted coefficients can be used by themselves, or input into human heat balance equations to predict relative performance differences under specific environmental conditions of wind speed, relative humidity, and environmental temperature.

In general, the lightweight Airplane Cotton fabric and the FRACU Type IV showed the best performance in terms of lowest resistance to heat and mass transfer, followed by the FR ACU Type III and the MCCUU LW NyCo. Sigma Versatech, Micro-Cotton, and ACU NyCo all had very similar relatively higher resistance to heat and mass transfer (i.e., less comfortable).

This document reports research undertaken at the U.S. Army Natick Soldier Research, Development and Engineering Center, Natick, MA, and has been assigned No. NATICK/TR- 17/012 in a series of reports approved for publication.

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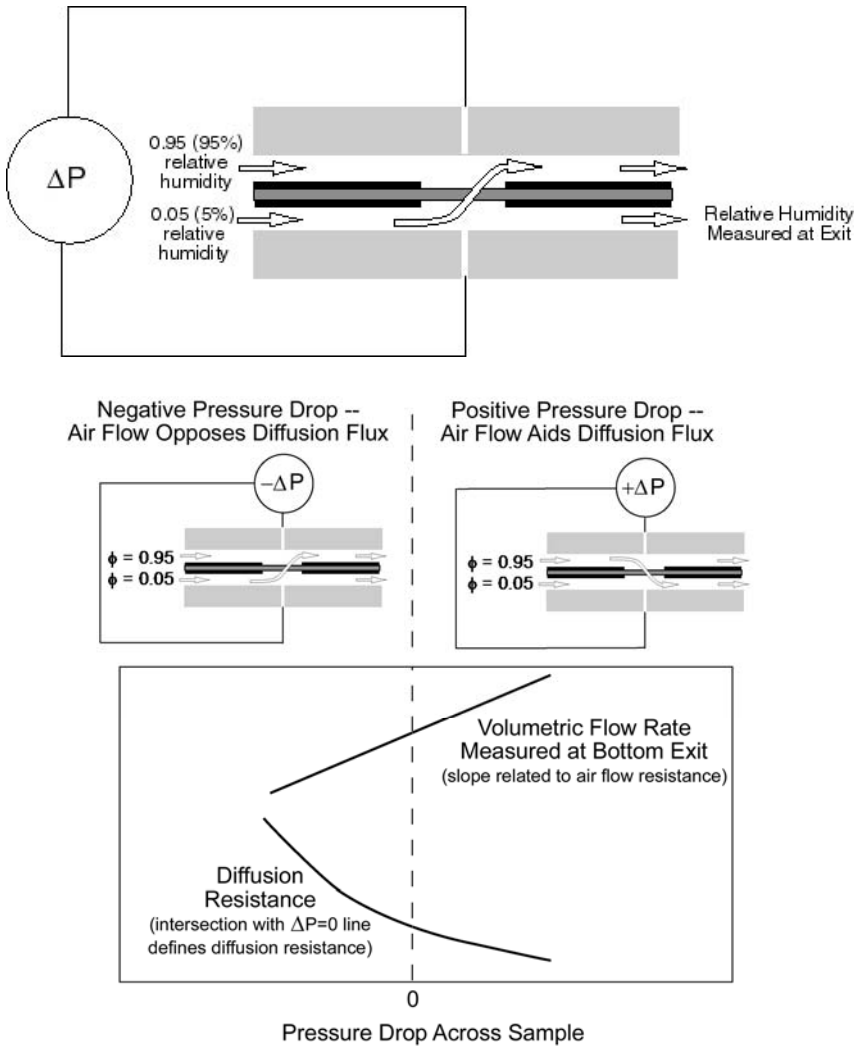
Appendix A
Dynamic Moisture Permeation Cell -- Diffusion/Convection Method

This test method measures water vapor diffusion resistance and air permeability (i.e., resistance to air flow) from the same test. A schematic of the test setup is shown below in Figure A-1; more details are in reference [3]. In this test method, the pressure drop across the sample is systematically changed to get different air flows through the fabric. For an air-impermeable fabric, there is no air flow, and the results do not change. But, if the fabric is air-permeable, there are large differences between various fabrics. Because there is a humidity difference across the sample, the water vapor diffusion property can be obtained from this test. At the condition of 0 pressure drop, a water vapor diffusion resistance property is measured that correlates with properties measured via the sweating guarded hot plate (ISO 11092) or the ASTM E96 methods.



Note: Air can flow across the fabric in either direction depending on the particular pressure drop set by the computer.

Figure A-1. Schematic of Convection/Diffusion Test.

Test Conditions – Water Vapor Diffusion/Convection
Temperature = 30 °C
Sample area = 10 cm^2
Flow rates on top and bottom = 2000 cm^3/minute
Humidity on top = .95 (95%); Humidity on Bottom =.05 (5%)
Pressure drop varied in increments between approximately –150 to 150 Pa.
Note: Humidity of 1.0 = 100%; (0.5 inches of water is about 125 Pa).

Calculating Air Permeability from Air Flow Resistance

The flow resistance (R) is defined as:

$R = (A\Delta p)/(\mu V)$

A = apparent sample flow area (m^2)
Δp = pressure drop across sample (Pa)
μ = gas viscosity (17.84 x 10-6 kg/m-s for air or N2 at 20°C)
V = total volumetric flow rate (m^3/s)

To convert from flow resistance in units of 1/m (m^{-1}) to air permeability as used in the textile industry ($m^3/s\text{-}m^2$, or $ft^3/min\text{-}ft^2$), where the pressure drop is usually 0.5 inches of water:

Q_{metric} ($m^3/s\text{-}m^2$) = $\Delta p/R\mu$

Δp = pressure drop in Pa (N/m^2); Frazier air permeability uses 125 Pa (0.5 inches of H20)
R = air flow resistance (1/m); value obtained from DMPC measurement
μ = air/N_2 viscosity (17.85 x 10^{-6} kg/m-s at 20°C)

$Q_{english}$ ($ft^3/min\text{-}ft^2$), sometimes called "CFM," cubic feet per minute) = 197 Qmetric

$Q_{english}$ ($ft^3/min\text{-}ft^2$), sometimes called "CFM," cubic feet per minute) = 1.3796 x109 / R

R is the air flow resistance as measured in the DMPC system (units of 1/m or m^{-1}).

Appendix B
Modeling Parameters

The specific version of the Individual Protection System Performance Model used for these simulations was “IP SPM v1.1 Beta 4,” (Copyright 2008-2013 Creare Inc.).

Model parameters include those associated with the clothing layers, with the human figure geometry and the air spaces between the skin surface and the clothing, and the external environment (wind, temperature, humidity, solar radiation).

Activity: Stationary

Anatomic Build: Newton, Fine (geometry based on the Newton Manikin form)

Challenge: Scenario E (no challenge). The challenge refers to the chemical warfare agent challenge. Because this simulation is only for thermal and water vapor transport, no chemical warfare agent challenge is necessary.

Ensemble: Standard Air Permeable Suit. The ensemble consists of boots, pants, and shirt, with a defined gap between the skin surface and the fabric surface of 10 mm.

Environment: Cornell Climate Chamber. The environmental conditions used for the clothed manikin simulations were 20 °C, 50% r.h., and wind speed as set by the individual model conditions (varying between 0.25 and 20 mph).

Simulation Options and Solver Parameters: Various details of simulation times, solver time steps, and grid resolution. The option set used for these simulations were “USARIEM Simulation Options Wet – Fine.” Skin temperature was set to 35 °C, skin emissivity is 0.98, and skin humidity = 100% (wet skin).

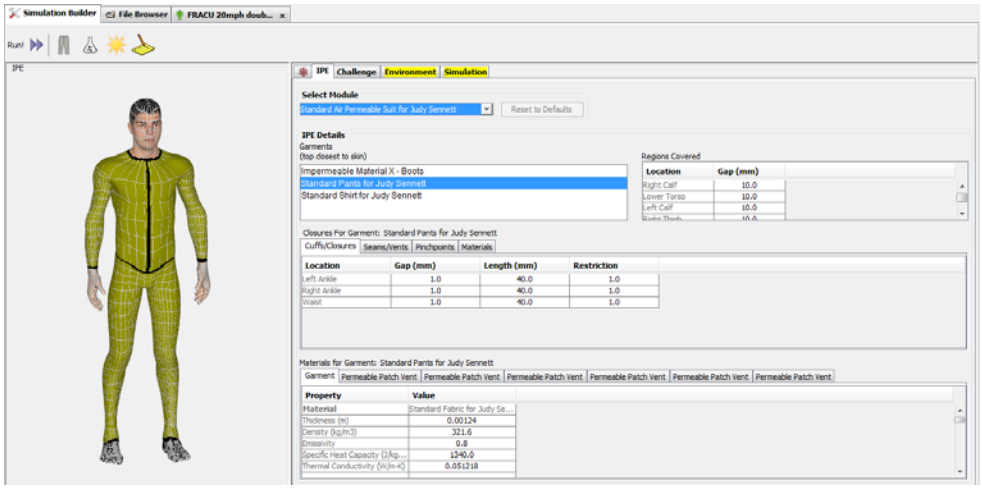


Figure C-1. Sample Graphical User Interface for Clothing Layer Model for Creare Individual Protection System Performance Model (IP SPM).

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Appendix C
Property Conversions for Parameters Required in IP-SPM

Water Vapor Transport Property (Breathability)

IP SPM Option that Assumes Constant Effective Diffusivity for D_{water} (m^2/s)

From IP SPM:
--Example for Wool Fabric:
$D_{water} = 8 \times 10^{-6}$ m^2/s
Thickness = 5×10^{-4} m

For DMPC-type Measurements:
Diffusion Resistance R_f (s/m) = $\Delta x / D_{water}$ = 62 s/m for wool layer

For Sweating Guarded Hot Plate-type Measurements:
R_f (s/m) = $R_{et} (M_w \Delta H_{vap} / RT)$
Note - neglecting temperature dependence, T = 35°
M_w = molecular weight of water (18 kg/kgmole)
ΔH_{vap} = enthalpy of vaporization for water (2.42×10^6 J/kg @ 35°C)
R = universal gas constant (8314.5 N-m/kgmole-K)
T = Temperature (K) (assume at 35°C or 308K)
or
$R_{et} = R_f / (M_w \Delta H_{vap} / RT) = (\Delta x \, RT) / (D_{water} \, M_w \Delta H_{vap})$ = 3.7 m^2-Pa /Watt for wool layer

For Cup-Type Measurements (for ASTM E96-80, Procedure B):
R_f (s/cm) = d_{eq}/D; so Rf (s/m) = 0.01* d_{eq} /D
D = diffusion coefficent of water in air (at 296 K, 23°C) = 0.256 cm^2/s
d_{eq} (cm) = (2300/MVTR)-d_{sa}
d_{sa}= still air layer under fabric in cup (assume 1.9 cm)
MVTR = measured flux from ASTM E96-80, in g/m^2/day
$D_{water} = \Delta x / R_f$

IP SPM Input:

DMPC: Given R_f (s/m):
$D_{water} = \Delta x / R_f$

SGHP: Given R_{et} (m^2-Pa/Watt):
$D_{water} = (\Delta x \, RT) / (R_{et} \, M_w \Delta H_{vap}) = (5.88 \times 10^{-2}) [(\Delta x) / (R_{et})]$

Air Flow Property (Air Permeability or Airflow Resistance)

IP SPM Option that Assumes Constant Airflow Resistance R_D (1/m)

From IP SPM:
--Example for Wool Fabric:
R_D = apparent Darcy flow resistance = 1×10^8 m^{-1}
Thickness = 5×10^{-4} m

For DMPC-type Measurements:

IP SPM uses same units as DMPC (1/m), so no conversion is needed: $R_D = 1 \times 10^8$ m^{-1}

For Textile Air Permeability Measurements:
Volumetric Flow Q ($m^3/s\text{-}m^2$) = $\Delta p/R_D\mu$

Δp = pressure drop in Pa (N/m^2)
standard Frazier textile air permeability (CFM) uses Δp = 125 Pa (0.5 inches of H_2O)
μ = air or nitrogen viscosity (17.85×10^{-6} kg/m-s at 20°C)

Convert to English units: CFM ($ft^3/min\text{-}ft^2$), sometimes called cubic feet per minute)

CFM=197 $\Delta p/R_D\mu$ = 13.8 $ft^3/min\text{-}ft^2$

IP SPM Input:

DMPC (no conversion needed): Given R_D (1/m):

Airflow Resistance R_D (1/m): = R_D (1/m)

Frazier Air Permeability: Given CFM (ft^3/minute-ft^2):

Airflow Resistance R_D (1/m): = $(197\Delta p)/ (CFM\ \mu) = (1.38 \times 10^9) / CFM$

Thermal Transport Property (Thermal Resistance, Thermal Conductivity)

<u>IP SPM Uses Thermal Conductivity and Thickness for each Clothing Layer k (W/m-K)</u>

From IP SPM:
--Example for Wool Fabric:
k = 0.043 W/m-K
Thickness = 5×10^{-4} m

For Thermal Resistance Measurements:
Thermal Resistance R_c (m^2-K/Watt) = $\Delta x / k$ = 0.0116 m^2-K/Watt for wool layer

For "Clo"Units:
Thermal Resistance R_c (clo) = $(6.461)\Delta x / k$ = 0.0751 clo for wool layer

IP SPM Input:

Given R_c (m^2-K/Watt):

$k = \Delta x / R_c$

Given R_c (clo):

$k = (6.461)\Delta x / R_c$

Note that for many simulations, the exact material thickness is not necessary, but the values of thermal conductivity and thickness must be chosen to give the correct thermal resistance.