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EFFECTS OF HEAT AND MOISTURE TRANSFER PROPERTIES OF FABRIC ON HEAT STRAIN IN CHEMICAL PROTECTIVE ENSEMBLES

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USARIEM TECHNICAL REPORT T17-10

EFFECTS OF HEAT AND MOISTURE TRANSFER PROPERTIES OF FABRIC ON HEAT STRAIN IN CHEMICAL PROTECTIVE ENSEMBLES

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At the request of US Army Natick Soldier Research, Development & Engineering Center (NSRDEC) Chemical Sciences & Engineering Team, the US Army Research Institute of Environmental Medicine (USARIEM) Biophysics and Biomedical Modeling Division has analyzed the effect of swatch thermal properties on ensemble thermal properties and predicted human thermoregulatory responses. This report is a summary of those findings. The report reviews factors affecting human body thermal balance, including fabric and clothing biophysics; analyzes the relationships among fabric thermal properties, ensemble thermal properties and endurance times; and proposes a pathway forward to reduce heat strain in PPE.

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EXECUTIVE SUMMARY

The barrier components of CB (Chemical/Biological) protective materials have been considered one of the major obstacles to reducing thermal burden of personal protective equipment (PPE). However, improvements in material properties at the swatch level have not always translated into similar improvements in ensembles at the system level nor have the improvements resulted in a significant reduction in heat strain during human physiological studies. At the request of US Army Natick Soldier Research, Development & Engineering Center (NSRDEC) Chemical Sciences & Engineering Team on behalf of Defense Threat Reduction Agency (DTRA), the US Army Research Institute of Environmental Medicine (USARIEM) Biophysics and Biomedical Modeling Division has analyzed (A) the relationship between thermal properties of eight CB protective fabric composites and fourteen CB protective ensembles, (B) the relationship between swatch thermal properties and predicted endurance times relative to heat strain in CB protective clothing at four environmental conditions. The objective is to gain better understanding of the role that fabric thermal properties play in impeding heat loss and exacerbating heat strain. This report is a summary of our findings.

The eight materials samples consist of seven prototype chemical protective materials and one traditional material (baseline). Each of the fourteen ensembles includes typical chemical protective clothing which is made from a single material with other protective equipment, e.g., Improved Outer Tactical Vest (IOTV), mask, gloves and overboots. The fabric samples were tested on a Sweating Guarded Hot Plate (SGHP) to measure fabric thermal and evaporative resistance, respectively. The ensembles were tested on a thermal manikin to measure ensemble thermal and evaporative resistance, respectively. The intrinsic fabric thermal and evaporative resistances ranged from 0.01 to 0.05 $m^2 \cdot °C \cdot W^{-1}$ and from 3.84 to 12.82 $m^2 \cdot Pa \cdot W^{-1}$, respectively. Intrinsic ensemble thermal and evaporative resistances ranged from 0.16 to 0.29 $m^2 \cdot °C \cdot W^{-1}$ and 27.05 to 65.15 $m^2 \cdot Pa \cdot W^{-1}$, separately. Material properties contribute ~10.6% of the thermal resistance and ~14.5% of the evaporative resistance of these fourteen multi-layer ensembles in the report. If thermal properties were the

same as the baseline fabric (intrinsic thermal and evaporative resistances 0.02 $m^2 \cdot °C \cdot W^{-1}$ and 3.84 $m^2 \cdot Pa \cdot W^{-1}$ respectively), the intrinsic ensemble thermal and evaporative resistances of the fourteen ensembles would reduce by only 2.7% and 6.7%, respectively.

The results show that an improvement in material thermal properties will result in either a slight change or no difference in thermal properties of the fourteen multi-layer ensembles. The thermal properties of a multi-layer ensemble are a result of the combined effects of every layer or component in the ensemble as well as the garment design of the ensemble itself. Therefore, it is important to continue to improve the thermal properties of individual protective materials, but it may be more beneficial to focus efforts on identifying ways to modify and manipulate complete ensembles to reduce the thermal burden in the protective ensembles.

Predicted endurance times at a 400 W metabolic rate are affected by swatch thermal and evaporative resistances, but the effects are dependent on environmental conditions. Thus, an improvement in swatch thermal properties may or may not result in any differences in observed physiological responses during human studies.

Six of the fourteen ensembles included the IOTV. Wearing the IOTV increases thermal burden by increasing thermal and evaporative resistances, which increases the metabolic cost of locomotion by increasing mass carried, and by impeding sweat evaporation from the torso.

INTRODUCTION

Protective material and garment developers face the on-going challenge of reducing the heat strain experienced by individuals wearing personal protective equipment (PPE). PPE, e.g., protective clothing, is designed to protect against chemical, biological, radiological, nuclear and explosive (CBRNE) threats and other physical hazards that may be encountered during military or industrial operations. For military applications, PPE often includes chemical/biological (CB) protective clothing, helmet, CB protective mask, outer gloves and boots, and body armor, e.g. the Improved Outer Tactical Vest (IOTV). The use of PPE can create significant physiological and physical stresses for wearers, and may impair vision, mobility, and communication. Generally the risks imposed by PPE increase as the level of protection increases.

Each individual layer of a PPE system makes a specific contribution towards the overall level of protection, but simultaneously contributes to heat strain through increases in thermal and evaporative resistance, increases in metabolic heat production associated with its mass, or both effects (1). An increase in ensemble mass may result in significant increases in metabolic heat production during exercise (2, 3) which may exacerbate the heat strain experienced when wearing PPE.

The barrier material used for PPE has been considered one of the major obstacles to improving thermal performance. These can include, but are not limited to, membranes, sorptive fabrics, and aerosol filtration materials. Material properties at the swatch level (e.g., thermal resistance, evaporative resistance, and thickness) have improved over time. However, these improvements at the swatch level have not always translated into similar improvements at the system level, or resulted in a significant reduction in heat strain during human physiological studies. Fabric thermal properties are only one of the factors contributing to the thermal burden of PPE and it is not clear to what extent they affect ensemble thermal properties and heat strain.

At the request of US Army Natick Soldier Research, Development & Engineering Center (NSRDEC) Chemical Sciences & Engineering Team, the US Army Research Institute of Environmental Medicine (USARIEM) Biophysics and Biomedical Modeling Division has analyzed the effect of swatch thermal properties on ensemble thermal properties and predicted human thermoregulatory responses. This report is a summary of those findings. The report reviews factors affecting human body thermal balance, including fabric and clothing biophysics; analyzes the relationships among fabric thermal properties, ensemble thermal properties and endurance times; and proposes a pathway forward to reduce heat strain in PPE.

METHODS

BODY HEAT BALANCE WHILE WEARING PROTECTIVE ENSEMBLE

Thermal burden is the excess heat storage by the human body attributed to the combined effect of clothing, activity, and environment. Excess thermal burden compromises physical and mental performance and increases the likelihood of heat casualties. CB protective ensembles significantly increase thermal burden, primarily by restricting heat loss by sweat evaporation and by increasing metabolic heat production.

The conceptual heat balance equation for the human body is expressed as:

$$S = M - W - R - C - K - E \qquad \text{(Eq. 1)}$$

where *S* is the rate of heat storage, *M* is the rate of metabolic heat production, *W* is the rate of the mechanical work, *R* is the rate of radiative heat loss, *C* is the rate of convective heat loss, *K* is the rate of conductive heat loss, *E* is the rate of evaporative heat loss. All values are expressed in $W \cdot m^{-2}$. *M*-*W* is always positive, with *W* being about 20% or less of *M*. In other words, only about 20% of the metabolic heat production goes to useful work for physiological processes such as pumping blood, and physical activities such as climbing stairs or digging a hole. The remaining 80% or more of metabolic heat production must be dissipated in order to maintain heat balance (S=0) and avoid excess heat storage (S>0). *R, C*, and *K* are the dry or sensible heat transfer avenues; the driving force is the temperature gradient between skin and environment. *E* is the evaporative or insensible heat transfer avenue where the driving force is the vapor pressure gradient between skin and environment.

The energy balance equation shows that the thermal burden experienced by Warfighters is mainly determined by three factors:

- Thermal resistance (insulation) and evaporative resistance (water vapor permeability) of the garment: each item on the body increases the thermal and evaporative resistance, e.g., protective clothing, masks, gloves, backpack;
- Metabolic heat production: each item or component (e.g., a fabric layer, combat load, body armor (IOTV)) on the body increases total weight carried and thus increases work rate and metabolic heat production during exercise;
- Environmental conditions: air temperature, air velocity, relative humidity, and radiant (solar) load.

HUMAN ENDURANCE TIME (ET)

Body temperature is associated with the rate of body heat storage (4):

$$T = T_{ref} + \int_0^t \frac{S}{mC_p} dt \qquad \text{(Eq. 2)}$$

where T is the mean body temperature in °C, T_{ref} is the reference body temperature at the thermal neutral condition (e.g., 27°C for a sedentary person with light clothing), t is time in seconds, m is the body mass in kg, and C_p is the specific heat of the body in $KJ \cdot °C^{-1} \cdot kg^{-1}$. The mathematical definition of the thermal burden is a positive rate of heat storage, $S>0$. The body accumulates heat when heat production exceeds heat dissipation ($S>0$); body temperature rises continuously according to Eq. 2 and eventually reaches a threshold value where a Soldier may become a heat casualty.

The risk of heat casualty increases significantly when the body temperature reaches or exceeds the threshold value. The endurance time (*ET*), which is the time needed to reach a core temperature of 39°C, is selected to represent the thermal burden threshold. Endurance time is an indicator of the time limit that a Warfighter can work in warm or hot environment without a significant risk of becoming a heat casualty.

SWATCH LEVEL THERMAL AND EVAPORATIVE RESISTANCE

Heat and mass transfer through fabric composites is a complicated process (5, 6). From the perspective of ensemble thermal properties, the outcome of this complex transport process is described by the thermal and evaporative resistance. A brief review of fabric thermal and evaporative resistance may be useful in understanding the relationships of material characteristics to ensemble thermal and evaporative resistance.

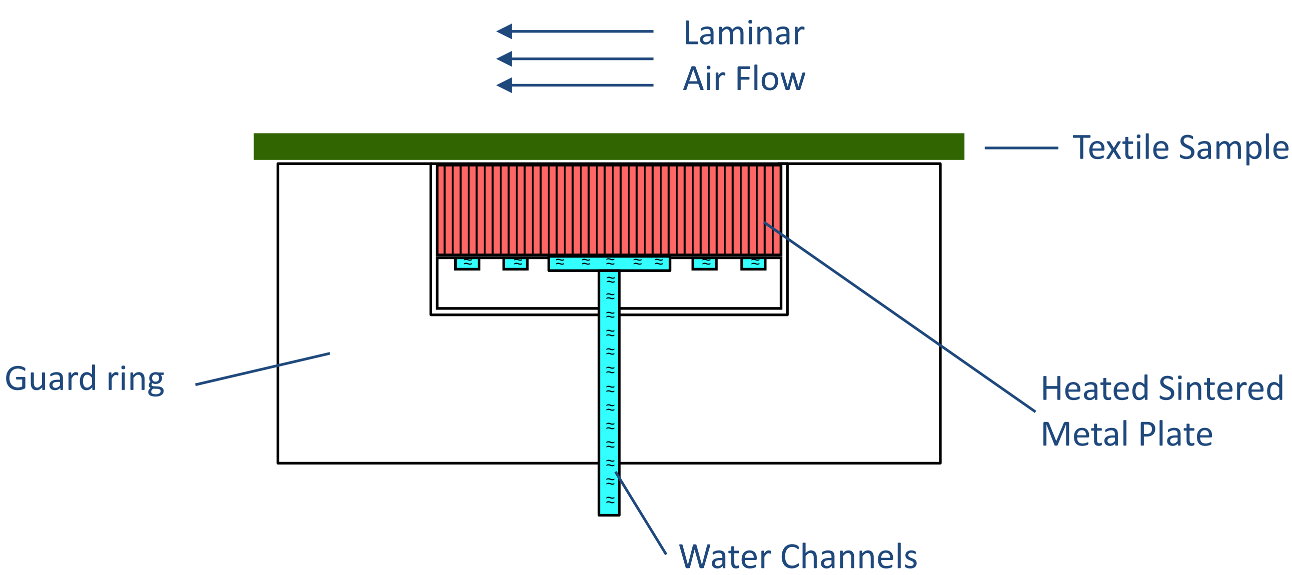
The thermal resistance of various fabrics are approximately proportional to the thickness of the fabric (7, 8), as air trapped within the fabric is a major factor determining the dry heat transfer properties of the material. Measurements on a sweating guarded hotplate (SGHP) show that fabric thermal resistances range from 0.1 to 1.4 $m^2 \cdot °C \cdot W^{-1}$ (0.65 to 9.0 clo) for fabric with thicknesses from ~ 2.0 to 56 mm (7). This indicates that fabric thermal resistance is roughly 0.024 $m^2 \cdot °C \cdot W^{-1}$ per mm thickness or 0.17 clo/mm. This is consistent with the number used to estimate thermal resistance from fabric thickness, 4 clo per inch (0.16 clo/mm) (7, 9).

Fabric evaporative resistance is not just related to thickness, but to many other factors, e.g., materials and fiber types. Clothing fibers are obstacles to vapor diffusion through fabrics, and the protective components in CB fabric composites (including but not limited to sorptive materials, membranes and aerosol filtrative layers) can reduce or even stop vapor diffusion (impermeable). Thus the evaporative resistance of a fabric composite is hard to estimate accurately from the thickness, and is usually measured on a SGHP.

SWEATING GUARDED HOT PLATE (SGHP)

The SGHP is a device that measures the thermal and evaporative resistance of a fabric or textile material. The SGHP assembly typically consists of test plate, a lateral thermal guard surrounding the perimeter of the test plate and a lower thermal guard (see Figure 1 for a typical SGHP construction). The two thermal guards ensure that all heat added to the test plate is transmitted through the material on the SGHP surface. All zones are independently controlled to the same set-point temperature. Test specimens are placed on the SGHP surface, covering the entire test plate and lateral thermal guard ring. When sweating is simulated for the measurement of evaporative resistance, it is first necessary to fit a liquid barrier over the entire SGHP surface. The liquid barrier is typically an untreated cellophane film that maintains a thin layer of liquid water between the surface of the SGHP and the barrier, allowing the transmission of water vapor through the film and test specimen while preventing liquid water from touching the textile specimen. The water required for this method is delivered to the plate assembly by a gravity feed reservoir. The water is preheated within the SGHP assembly and eventually dispersed on the plate surface through an array of small pores.

Figure 1 Schematic of Sweating Guarded Hot Plate (drawing from Mr. T Endrusick)



ASTM F1868-14 provides detailed specifications for the measurement of the thermal and evaporative resistances under steady-state conditions of fabrics, films, coatings, foams, and leathers - including multi-layer assemblies - used in clothing systems (10). The test specimen remains flat against the plate and covers entire active thermal zone. The SGHP is installed inside a test chamber and each zone in the hot plate assembly is set at a constant temperature of 35°C. For Procedure Part A—Thermal Resistance, the environmental conditions are set to an ambient temperature between 4°C and 25°C with the selected set point maintained within ±0.1°C, and a relative humidity between 20% and 80% with the selected set point maintained within ±4%. For Procedure Part B—Evaporative Resistance, the setpoints are more stringent than Part A with a prescribed ambient temperature of 35°C ± 0.1°C and a relative humidity at 40% ±4%. Both Part A and Part B specify an air velocity between 0.5 m/s and 1.0 m/s to be maintained within ± 0.1 m/s.

SYSTEM LEVEL TOTAL THERMAL AND EVAPORATIVE RESISTANCE

The impact of the garment on heat transfer from the body to the environment is described by two parameters: the total ensemble thermal resistance (R_t) in $m^2 \cdot °C \cdot W^{-1}$ or clo (1 clo = 0.155 $m^2 \cdot °C \cdot W^{-1}$) and the total ensemble evaporative resistance (R_{et}) in $m^2 \cdot Pa \cdot W^{-1}$. R_t is the resistance to dry heat transfer by way of conduction, convection, and radiation, and describes the effect of the clothing on the dry heat transfer from the skin to the environment. The evaporative resistance is the resistance to evaporative heat transfer from the body to the environment and describes the effect of clothing on the evaporative heat transfer from the skin to the environment. Both ensemble thermal and evaporative resistances are usually determined on a thermal manikin.

When clothing is worn, the dry and evaporative heat loss from the body surface to the environment is described by:

$$R + C = \frac{T_s - T_o}{R_t} \ [\mathrm{W \cdot m^{-2}}] \qquad \text{(Eq. 3)}$$

$$E = w \cdot \frac{P_{sk,s} - P_a}{R_{et}} \ [\mathrm{W \cdot m^{-2}}] \qquad \text{(Eq. 4)}$$

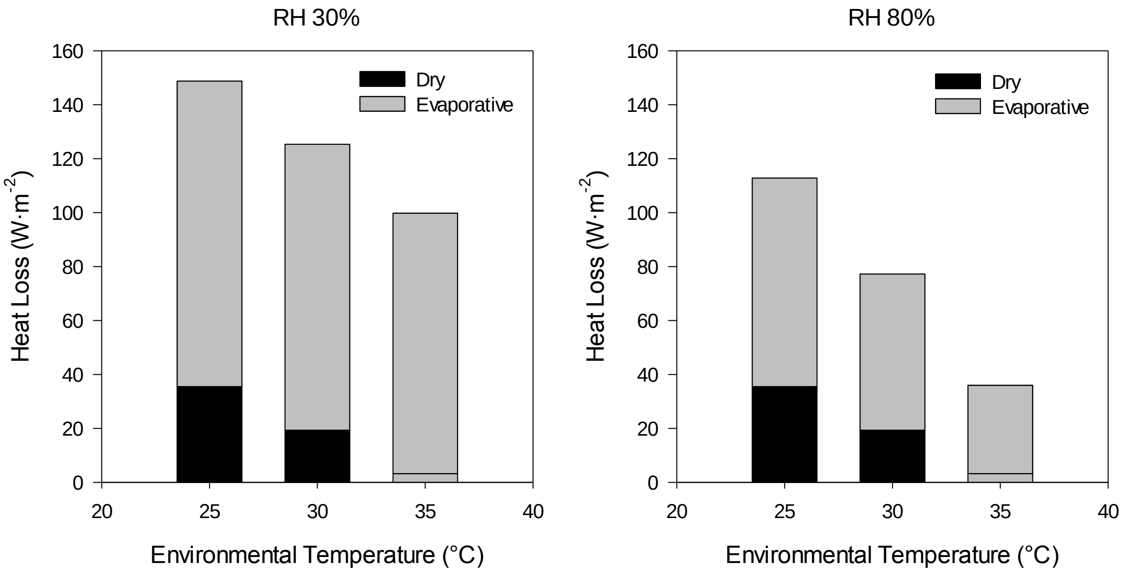
where T_s is the skin temperature °C; T_o is operative temperature °C; w is a dimensionless parameter to describe how wet the skin is: 0 for dry skin, and 1 for completely wet skin; $P_{sk,s}$ is water vapor pressure at skin in Pa; P_a is water vapor pressure of the ambient environment in Pa. T_o is defined as:

$$T_o = \frac{h_c \cdot T_a + h_r \cdot T_r}{h_c + h_r} \qquad \text{(Eq. 5)}$$

where h_c and h_r are the convective and radiative heat transfer coefficients respectively, in $W \cdot °C^{-1} \cdot m^{-2}$. T_a is the ambient temperature, and T_r is the ambient radiation temperature, both in °C. When the T_a and T_r are assumed to be the same, T_o is equal to T_a.

Eq. 3 and 4 clearly show how clothing attenuates heat loss from the skin surface to the environment. In a warm or hot environment, as the difference between the skin and ambient temperature decreases, the dry heat loss defined by Eq. 3 also decreases. As a result, the evaporative heat loss defined by Eq. 4 becomes the major, or often the only avenue for heat loss. Figure 2 is an example of dry and wet heat loss when the T_s is assumed to be 36°C and environmental temperatures are 25, 30 and 35°C. The evaporative heat loss clearly becomes the dominant heat loss avenue when environmental temperature increases and consequently reduces the dry heat loss potential. Therefore, for the purpose of alleviating heat strain in CB clothing, the evaporative resistance is generally a more important parameter than the thermal resistance.

Figure 2 Estimated potential body heat loss*



* 36°C skin temperature; 25, 30, and 35°C ambient temperature, 30 and 80% relative humidity (RH), 0.4 $m \cdot s^{-1}$ air velocity; R_t of 0.31 $m^2 \cdot °C \cdot W^{-1}$ and R_{et} of 64.8 $m^2 \cdot Pa \cdot W^{-1}$.

Often the moisture permeability index (i_m, dimensionless) is used to describe the effects of clothing on evaporation. The moisture permeability index is not directly measured on the manikin but calculated from the ensemble thermal and evaporative resistances:

$$i_m = \frac{R_t}{LR \cdot R_{et}} \qquad \text{(Eq. 6)}$$

where *LR* is the Lewis ratio, and equals ~0.0165 °C/Pa at typical indoor conditions. For example, the i_m for the battle dress uniform (BDU) or army combat uniform (ACU) is ~0.4-0.5 at a low air velocity of 0.4 $m \cdot s^{-1}$. Total heat loss from the body is calculated using Eq. 3, 4 and 6 together:

$$R + C + E = \frac{1}{R_t} \cdot (T_s - T_o) + \frac{i_m}{R_t} \cdot LR \cdot w \cdot (P_{sk,s} - P_a) \qquad \text{(Eq. 7)}$$

The concept of i_m/clo is derived from the term i_m/R_t in Eq. 7. As 1 clo is 0.155 W·°C^{-1}·m^{-2}, i_m/clo is rewritten as:

$$i_m/clo = \frac{0.155}{LR \cdot R_{et}} = \frac{9.394}{R_{et}} \qquad \text{(Eq. 8)}$$

At USARIEM, i_m/clo, the ratio of the ensemble's permeability index, has been referred to as the evaporative cooling potential, with higher values indicating a reduction in the thermal burden imposed on the clothed individual being studied. If thermal manikin tests indicate there is a large enough improvement (≥ 0.1 i_m/clo) between the control and a prototype ensemble, i.e., that it will be greater than the typical variability associated with human testing, it is usually recommended that the prototype ensemble be evaluated by human testing that incorporates adequate controls. When differences in thermal manikin tests are small (< 0.1 i_m/clo) and thus unlikely to produce significant differences in physiological strain during human testing, modeling alone may be used for further evaluation, especially if the design incorporates a unique feature or performance claim. However, human testing may still be requested to document the human physiological strain, even when comparisons are not likely to reveal significant differences. Such testing may ensure that unanticipated factors, which may or may not be thermal properties, will not significantly impact the user.

SYSTEM LEVEL INTRINSIC THERMAL AND EVAPORATIVE RESISTANCE

For convenience of analysis, the total ensemble thermal and evaporative resistance is further rewritten as:

$$R_t = R_{cl} + \frac{1}{f_{cl} \cdot h} = R_{cl} + \frac{1}{f_{cl}} \cdot R_a \qquad \text{(Eq. 9)}$$

$$R_{et} = R_{ecl} + \frac{1}{f_{cl} \cdot h_e} = R_{ecl} + \frac{1}{f_{cl}} \cdot R_{ea} \qquad \text{(Eq. 10)}$$

where R_{cl} is the intrinsic thermal resistance in $m^2 \cdot °C \cdot W^{-1}$; f_{cl} is clothing area factor, the dimensionless ratio of the clothed surface to body surface area; h is the heat transfer coefficient in $W \cdot °C^{-1} \cdot m^{-2}$; R_a is the thermal resistance of the boundary air layer in $m^2 \cdot °C \cdot W^{-1}$; R_{ecl} is the intrinsic evaporative resistance in $m^2 \cdot P_a \cdot W^{-1}$; h_e is the evaporative heat transfer coefficient in $W \cdot m^{-2} \cdot Pa^{-1}$; and R_{ea} is the evaporative resistance of the boundary air layer in $m^2 \cdot P_a \cdot W^{-1}$. R_a and R_{ea} are the values measured on nude manikins. Intrinsic ensemble thermal and evaporative resistances do not include the additional resistance provided by the boundary layer at the clothing surface, which is estimated by dividing the nude boundary air layer by f_{cl}. Therefore, the intrinsic ensemble thermal and evaporative resistances are created by the clothing itself as well as the air gap between the manikin surface, or skin, and the clothing. The effect of the boundary layer is determined primarily by external environmental conditions, often air velocity, and is minimally influenced by either the fabric or clothing design.

It is the intrinsic ensemble thermal and evaporative resistances that are influenced by the fabric and clothing design. For multi-layer or component ensemble systems, the intrinsic ensemble thermal and evaporative resistances are further expressed by:

$$R_{cl} = \sum R_{cf,i} + \sum R_{g,i} \quad \text{(Eq. 11)}$$

$$R_{ecl} = \sum R_{ef,i} + \sum R_{eg,i} \quad \text{(Eq. 12)}$$

where R_{cf} is the intrinsic fabric thermal resistance in $m^2 \cdot °C \cdot W^{-1}$, R_g is the thermal resistance provided by the air gaps between the skin and clothing surfaces in $m^2 \cdot °C \cdot W^{-1}$, and R_{ef} is the intrinsic fabric evaporative resistance in $m^2 \cdot P_a \cdot W^{-1}$, and R_{eg} is the evaporative resistance provided by the air gaps between the skin and clothing surfaces in $m^2 \cdot P_a \cdot W^{-1}$. If no air gap exists, the ensemble thermal and evaporative resistances are the sum of the intrinsic fabric thermal and evaporative resistances.

The intrinsic thermal and evaporative resistance is equal to the summation of all fabric and air layers between the skin and the environment. As mentioned before, thermal resistances are usually proportional to thickness, and each layer contributes to the total thermal resistance. However, evaporative resistance may contribute differently. If even one layer is impermeable, then the evaporative resistance of all layers will be impermeable.

The percentage contributions of the swatch material to the intrinsic ensemble thermal and evaporative resistances are defined by their fabric contribution:

$$fabric\ contribution\ to\ R_{cl}\ \% = \frac{R_{cf}}{R_{cl}} \cdot 100 \qquad \text{(Eq. 13)}$$

$$fabric\ contribution\ to\ R_{ecl}\ \% = \frac{R_{ef}}{R_{ecl}} \cdot 100 \qquad \text{(Eq. 14)}$$

The intrinsic ensemble resistances are calculated using Eq. 9 and 10. Intrinsic fabric resistances are calculated in the same manner but different subscripts of *R* are used to clearly distinguish between ensemble and fabric resistance. In Table 1, the notation in the fabric row can replace the ensemble row in Eq. 9 and Eq. 10. The f_{cl} for SGHP is 1.0, as the fabric samples and SGHP surface areas are the same. Because f_{cl} was not collected for this study, it is assumed that the area factors for PPE ensembles in this report are 1.2 (this is an estimated value for a similar PPE).

Table 1 Notation for fabric and ensemble resistances

	Total		Intrinsic		Boundary Air Layer	
	Thermal	Evaporative	Thermal	Evaporative	Thermal	Evaporative
Fabric	R_{ct}	R_{eft}*	R_{cf}	R_{ef}	R_{cbp}	R_{ebp}
Ensemble	R_t	R_{et}	R_{cl}	R_{ecl}	R_a	R_{ea}

*In ASTM standards F1868-14 and F2370-15, total fabric and ensemble evaporative resistance have the same notation, R_{et}. In this report, the total fabric evaporative resistance will be referred to as R_{eft} to differentiate.

When improvements are made to the fabric thermal and evaporative resistances of PPE materials, the ensemble thermal and evaporative resistances are also expected to improve. When the ensemble material is replaced by a material with better thermal properties and the ensemble design and configuration are the same, then the only items that change in Eq. 11 and 12 are the material properties. Thus the change in the intrinsic ensemble thermal and evaporative resistances can be estimated by:

$$\Delta R_{cl} = \Delta R_{f,i} \qquad \text{(Eq. 15)}$$

$$\Delta R_{ecl} = \Delta R_{ef,i} \qquad \text{(Eq. 16)}$$

THERMAL MANIKIN TESTING

USARIEM has a long history of measuring thermal and evaporative resistances of protective clothing ensembles, using standard operating procedures used before the development of industry standard test methods (11, 12). The experiments are conducted on a thermal manikin with a 50th percentile western male body form in a controlled environmental chamber. The computer-controlled thermal manikin is dressed with a tight, form-fitting suit. For measuring evaporative resistance, the suit is saturated with water to simulate a sweating human with 100% wetted surface area. The advantage of thermal manikin testing is that heat transfer characteristics of a complete ensemble are evaluated as the garment is designed to be worn. The testing thus accounts not only for the properties of the specific textiles, but also for garment design and the drape or fit on the manikin form, and the effect of any added individual combat equipment, such as body armor. Articulated manikins that simulate human locomotion can also measure the effect of air movement within the clothing microclimate on heat and water vapor transfer.

Standard procedures for operating the thermal manikin include regulating the manikin surface at a constant temperature, and controlling environmental conditions, such as the ambient temperature, relative humidity and air velocity in the climatic chamber housing the manikin. The most widely accepted test procedures for the operation of a thermal manikin are published by ASTM International (formerly American Society for Testing and Materials). ASTM F1291-15, "Standard Test Method for Measuring the Thermal Insulation of Clothing Using a Heated Manikin", which describes the measurement of the thermal resistance of a complete clothing ensemble (13). Some requirements of the procedure include a thermal manikin controlled at a mean surface temperature of 35 ± 0.2ºC and a climatic chamber controlled at an air velocity of

0.4 ± 0.1 m·s^{-1}. ASTM F1291-15 allows for some flexibility with the ambient conditions, with the air temperature specified to be at least 12°C below the thermal manikin's mean surface temperature and the relative humidity to be between 30 and 80%, but preferably 50%. At USARIEM, the typical ambient conditions for thermal resistance testing are 20 ± 0.5ºC, 50 ± 5% relative humidity. ASTM F 2370-05, "Standard Test Method for Measuring the Evaporative Resistance of Clothing Using a Sweating Manikin" measures the evaporative resistance of a complete clothing ensemble (14). Some requirements include the temperature of the thermal manikin surface to be controlled at 35 ± 0.5ºC and a climatic chamber controlled at 35 ± 0.5ºC, 40 ± 5% relative humidity, with a 0.4 ± 0.1 m·s^{-1} air velocity. In addition to the standard tests conducted at 0.4 m·s^{-1}, USARIEM frequently conducts tests at two higher air velocities to provide an accurate determination of the effect of increased air movement on the thermal transfer properties of the clothing (15). These data are necessary input values for multiple physiological models at USARIEM that predict human thermoregulatory responses under a variety of environmental conditions and work intensities.

MODELLING APPROACH

USARIEM has a well-established approach, using manikin testing and modeling, to support the development of new ensembles (1, 12, 16-18). This approach consists of two steps. First, the garment biophysics parameters, i.e., the ensemble thermal and evaporative resistances, are measured on the thermal manikin in controlled environmental chambers. Second, those thermal and evaporative resistances as used as inputs to thermoregulatory models that predict human thermal responses to various combinations of physical activities and environmental conditions. This approach interprets ensemble design and garment biophysical properties, using physiological terminology, thus allowing garment and materiel developers to understand how their designs will affect human thermal responses.

Currently, the two main thermal models for ensemble evaluations are an empirical model, the Heat Strain Decision Aid (HSDA) (19, 20), and a rational model, the six-cylinder thermoregulatory model (SCTM) (21). General model inputs and outputs are as follows:

- **Model inputs**
  - Anthropometric characteristics (i.e., height, weight, body fat %)
  - Metabolic rate
  - Clothing parameters (i.e., insulation and moisture permeability index)
  - Environmental conditions (e.g., temperature, humidity, air velocity)

- **Model outputs**
  - Temperatures, e.g. the core temperature and skin temperatures
  - Sweat rates
  - Water requirements
  - Likelihood of heat casualties
  - Maximum endurance time and optimal work/rest cycle

Heat Strain Decision Aid (HSDA)

HSDA is an empirical model derived from an extensive database of human studies and incorporates the biophysics of heat exchange (16, 19, 20). It predicts core temperature, maximum work times, sustainable work-rest cycles, water requirements, and the estimated likelihood of heat casualties. This model has been used to support development of guidance and doctrine for the military (22) and has been used extensively by USARIEM to evaluate heat strain of protective clothing (17, 18).

Six Cylinder Thermoregulatory Model (SCTM)

SCTM is a rational model, validated extensively using data on physiological responses to heat and cold stress in individuals performing a variety of activities at different exercise intensities, and while wearing various clothing ensembles (21, 23). In this model, the human body is subdivided into segments representing the head, trunk, arms, legs, hands, and feet. Each segment is subdivided into concentric compartments representing the core, muscle, fat, and skin. The integrated signal to the thermoregulatory controller is composed of the weighted inputs from thermal receptors at various sites distributed throughout the body. In order to maintain homeostasis, thermoregulatory actions (e.g., vasomotor changes, metabolic heat production, sweat rate) are activated by the body in response to differences between its setpoint and the integrated thermal signal received by the thermoregulatory controller.

An advantage of SCTM is that it takes into account the regional differences in thermal and evaporative resistances (i.e., head, torso, arm, hand, leg and foot), thus predicting the effects of regional resistances on human thermal responses. This model has been used to quantify the effects of thermal and evaporative resistance and weight of a PPE system, layer by layer, on human thermal responses (1). SCTM has also been used to simulate human thermoregulatory responses while wearing liquid cooling garments (24, 25).

MATERIALS AND GARMENTS EVALUATED

The Integrated Protective Fabric System (IPFS) program, funded by DTRA and executed by the NSRDEC, has designed several novel CB protective materials and garments to explore the trade space between protection and thermal burden in order to transition the results to the Uniform Integrated Protective Ensemble (UIPE) Increment II acquisition program. The materials and garments evaluated are designed to serve different mission scenarios with varying challenge levels and durations.

CBEC (CHEMICAL/BIOLOGICAL EMERGENCY COVERALL)

The CBEC garment was designed to be donned in an emergency situation, worn over the ACU. As the garment should be donned quickly, the design is a one piece with simple closures, seen in Figure 3. Since the mission scenario is for limited use, the design is stripped down with no pockets. The garment material is a thin trilayer composite with a lightweight ripstop woven cover fabric, 4.0 ounces per square yard (osy) on top with a liquid repellent finish. Laminated to the cover fabric is a microfiber nonwoven layer (for aerosol protection) with carbon beads sandwiched in between the microfiber layer and the woven cover fabric. The total weight of the fabric composite is

7.8 osy, a very lightweight material system. However, this CB protective system is worn over the FRACU, which adds weight and thermal and evaporative resistance to the total ensemble performance.

Figure 3 Picture of CBEC prototype and concept sketch.

CBFRACU (CHEMICAL BIOLOGICAL FLAME RESISTANT ARMY COMBAT UNIFORM)

The CBFRACU garment was designed to be a continuous use garment worn in place of the standard duty uniform, and thus the design was based off of the standard duty uniform with only PTs worn underneath. The garment is a two piece design, shown in Figure 4. The white areas of the garment are where a material composite is placed consisting of a flame resistant ripstop cover fabric with a microporous ePTFE (expanded polytetrafluoroethylene) aerosol protective liner laminated to the cover fabric. Below the cover fabric and attached at the sewn seams is an activated carbon cloth (5.5 osy). The total weight of the material composite is 12.4 osy. The blue areas of the garment show where just the activated carbon cloth was placed in order to improve the closures and interfaces of the garment. Zippers are incorporated into the design for active venting when in MOPP2 (Mission Oriented Protective Posture).

Figure 4 Picture of CBFRACU prototype and concept sketch.

CBCC TYPE A (CHEMICAL BIOLOGICAL COMBAT COVERALL)

The CBCC Type A garment serves the same mission scenario as the CBFRACU and utilizes the same materials. However, the garment is a one piece design instead of a two piece design. Zippers were incorporated into the design for active venting when in MOPP2.

Figure 5 Picture of CBCC Type A prototype and concept sketch.

CBCC TYPE B

Utilizing the same one piece design as the CBCC Type A, the CBCC Type B is also intended to be a continuous use garment worn in place of the standard duty uniform, and thus the design was based off of the standard duty uniform with only PTs worn underneath. The difference between the Type A and the Type B is the materials used. The Type B garment system is made of two material composites placed strategically in the garment, shown in Figure 6. The white areas, comprising the majority of the garment, have a fabric composite with a thin flame resistant (FR) ripstop cover fabric (4.9 osy) and a semi-permeable membrane laminated to a thin tricot next-to-skin knit liner (4.6 osy). The green areas are air permeable to allow for a release of pressure build up within the suit. The fabric composite has the same cover fabric laminated to an ePTFE microporous aerosol protective liner (total 5.2 osy), with an activated carbon cloth underneath (5.5 osy).

Figure 6 Picture of CBCC Type B prototype and concept sketch.

EFRACU-CBUG (ENHANCED FLAME RESISTANT ARMY COMBAT UNIFORM – CHEMICAL BIOLOGICAL UNDERGARMENT)

The EFRACU-CBUG is a dual garment system with a two piece outer garment and two piece CB protective undergarment, seen in Figure 7. The EFRACU-CBUG design was also intended to be a continuous use garment, worn instead of the ACU. The undergarment is made of a tri-layer fabric with a cotton/elastane jersey knit next to the skin, a nylon tricot knit facing outwards, and carbon beads sandwiched in between the two layers. The composite weighed 7.0 osy. The fabric of the outer jacket and pants are a woven ripstop flame resistant blend laminated to an ePTFE microporous aerosol protective liner. The outer fabric composite weighed 6.9 osy.

Figure 7 Picture of EFRACU-CBUG prototype and concept sketch.

COMPARISON TO THE CB BASELINE GARMENT

All of the garments developed within the IPFS program used lighter weight materials than those used in the baseline garment, and utilized a more conformable, less bulky design with improved closures and interfaces designed to improve system level vapor and aerosol protection. Some garment designs, such as the CBFRACU, CBCC Type A, and EFRACU-CBUG, utilized zippers in order to lessen the thermal burden by incorporating the ability to open vents in MOPP2. The material and garment design approach resulted in a total weight reduction in each CB protective fabric system when compared to the baseline garment system. Even more gains in weight reduction were realized in comparison to the baseline CB garment worn over the FRACU, as it is sometimes worn. The weights are summarized in Table 2.

Table 2 Weight reduction of CB garment prototypes

Garment	Weight Reduction compared to Baseline (%)	Weight Reduction compared to Baseline-FRACU (%)
CBEC-FRACU	9	38
CBFRACU	19	45
CBCC Type A	26	49
CBCC Type B	43	61
EFRACU-CBUG	16	42

For ease of analysis and discussion, the fabrics of the ensembles have been coded, as shown inTable 3.

Table 3 Fabric Description

Fabric Code	Garment
Baseline	Baseline (2 separate layers)
Baseline-FRACU	Baseline - FRACU (3 separate layers)
M1-L1	CBCC Type A (2 separate layers)
M2-M4	EFRACU - CBUG (2 separate layers)
M3-FRACU	CBEC - FRACU (2 separate layers)
M5-L2	CBCC Type B non-air perm areas (2 separate layers)
M6-L3	CBCC Type B air perm areas (2 separate layers)

RESULTS

EFFECT OF MATERIAL ON ENSEMBLE BIOPHYSICAL PROPERTIES

The IPFS program has been aggregating data on fabric properties, ensemble properties, and HSDA predictions of endurance times to support their chemical protective ensemble research and development efforts. USARIEM analyzed the thermal property data of eight fabrics and fourteen ensembles as well as predicted endurance times for an individual wearing twelve ensembles and working at 400 W metabolic rate under Temperate, Hawaii, Jungle and Desert conditions.

The fabrics in Table 3 were tested on SGHP according to ASTM F1868-14 and the procedures described above. Ensembles in Table 4 and Table 5 were tested on thermal manikins according to ASTM F1291-15 and F2370-15, and the procedures described above. As detailed in Table 4 and Table 5 , the ensembles include chemical protective clothing which is made from the fabrics in Table 3 and other equipment for Soldiers, such as a backpack, hydration pack, and IOTV. In MOPP4, Soldiers wear CB protective boots and gloves, and don the CB protective mask.

Table 6 shows thermal resistances for each material and the corresponding MOPP4 thermal resistances. It also shows the fabric contributions and how the ensemble thermal resistance would be altered if the fabric was the FRACU. Based on the assumption that the clothing design and configurations are exactly the same, those changes were estimated using Eq. 15 and 16. The mean intrinsic fabric thermal resistance is 0.02 $m^2·°C·W^{-1}$ and the mean intrinsic ensemble thermal resistance is 0.23 $m^2·°C·W^{-1}$. Fabrics contribute about 10.6 % of the intrinsic thermal resistances of the entire ensembles. If the fabric was replaced by FRACU fabric, the ensemble thermal resistance would be reduced by only 2.7%, if the ensemble included CB protective equipment and the IOTV.

Table 7 shows evaporative resistances for each material, the corresponding MOPP4 evaporative resistances, fabric contributions and the changes in ensemble evaporative resistances if the ensemble fabric was replaced with the FRACU fabric. The mean intrinsic fabric evaporative resistance is 7.4 $m^2·P_a·W^{-1}$ and mean intrinsic ensemble evaporative resistance is 59.8 $m^2 \cdot P_a \cdot W^{-1}$. Fabrics contribute ~14.5% to the evaporative resistance of the ensemble. If the fabric was replaced by the FRACU fabric in the calculations, the ensemble evaporative resistances would be reduced by an average of ~6.7%. Fabric M1-L1 is the closest fabric to FRACU. If the M1-L1 fabric is nearly equivalent to the FRACU fabric, the evaporative resistance of CBFRACU or CBCC Type A would be reduced only by ~ 3.7%, since both ensembles consist of M1-L1 material.

Table 8 shows fabric and its corresponding MOPP2 ensemble thermal resistance. It also shows the fabric contributions and changes in intrinsic ensemble thermal resistance if the fabric was the FRACU fabric. The mean intrinsic fabric thermal resistance is 0.02 $m^2 \cdot °C \cdot W^{-1}$ and mean intrinsic ensemble thermal resistance is 0.21 $m^2 \cdot °C \cdot W^{-1}$. The fabrics contribute ~10.8% to the thermal resistance of the ensemble. If the fabrics were replaced by FRACU fabric, the ensemble thermal resistance would be reduced by only 2.4%.

Table 9 shows the fabric evaporative resistance, the corresponding MOPP2 ensemble evaporative resistance, fabric contributions and the changes in ensemble thermal resistance if the fabric was the FRACU fabric. The mean intrinsic fabric evaporative resistance is 11.9 $m^2 \cdot P_a \cdot W^{-1}$ and mean intrinsic ensemble evaporative resistance is 41.5 $m^2 \cdot P_a \cdot W^{-1}$. The fabrics contribute ~14.5% to the evaporative resistance of the ensembles. If the fabric was replaced by FRACU fabric, the ensemble evaporative resistance would be reduced by ~5.3%.

Three ensembles, the EFRACU+CBUG, CBFRACU, and FRACU with IOTV, have both the values for MOPP4 and for MOPP2. The differences between Table 6 and Table 8 and between Table 7 and Table 9 show the contributions of additional protective layers (e.g., a mask, overboots) and vent open to thermal and evaporative resistances. Figure 8 shows the relationship between fabric and ensemble MOPP4 thermal and evaporative resistances. Linear regression analysis shows the following relationship

$$R_t = 0.0824 + 2.4662 \cdot R_f \; (r = 0.79) \qquad \text{(Eq. 17)}$$

(Eq. 18)

$$R_{et} = 14.6014 + 3.4951 \cdot R_{ef} \ (r = 0.86)$$

This indicates that correlation between ensemble and fabric evaporative resistances is stronger than that between ensemble and fabric thermal resistances.

Figure 9 shows the relationships between the fabric and MOPP2 ensemble thermal and evaporative resistances. In general, the relationship between fabric and ensembles are similar. No statistical analysis was conducted, as there are only four data points with MOPP2 ensemble.

Table 4 Ensemble MOPP4 Description

Ensemble MOPP4	**Description**
CBEC - FRACU	CBEC over FRACU over t-shirt, boxers, green sock, IOTV, backpack, hydration pack, mask, mask carrier, load carriage belt, gloves, boots and overboots
EFRACU – CBUG (vents closed)	EFRACU over CBUG, vents closed, boxers, green socks, plate carrier, backpack, hydration pack, mask, mask carrier, load carriage belt, gloves, boots and overboots
CBCC Type B	CBCC Type B over t-shirt, boxers, green socks, IOTV, backpack, hydration pack, mask, mask carrier, load carriage belt, gloves, boots and overboots
Baseline	Baseline garment, t-shirt, boxers, green socks, plate carrier, backpack, hydration pack, mask, mask carrier, load carriage belt, gloves, boots and overboots
Baseline - FRACU	Baseline over FRACU, t-shirt, boxers, green sock, IOTV, backpack, hydration pack, mask, mask carrier, load carriage belt, gloves, boots and over boots
CBFRACU (vents closed)	CBFRACU over personal undergarments, vents closed
CBCC Type A (vents closed)	CBCC Type A over personal undergarments, vents closed
FRACU no IOTV	FRACU, t-shirt, briefs, green socks, tan belt, CB mask and hood, helmet, hatch gloves and desert tan boots, over boots
FRACU with IOTV	FRACU, IOTV, t-shirt, briefs, green socks, tan belt, CB mask and hood, helmet, hatch gloves, desert tan boots, over boots

Table 5 Ensemble MOPP2 Description

Ensemble MOPP2	Description
EFRACU - CBUG (vents open)	EFRACU over CBUG, vents open
CBFRACU (vents open)	CBFRACU over personal undergarments, vents open
CBCC Type A (vents open)	CBCC Type A over personal undergarments, vents open
FRACU with IOTV	FRACU FULL COMBAT LOAD: t-shirt, briefs, green socks, tan belt, helmet, sunglasses, desert tan boots

Table 6 Material Thermal Resistance and Ensemble Thermal Resistance in MOPP4

Fabric	Thermal Resistance, $m^2 \cdot °C \cdot W^{-1}$		Ensemble MOPP4	Thermal Resistance $m^2 \cdot °C \cdot W^{-1}$		Fabric contribution %	Change if fabric was FRACU fabric	
	Total (R_{ct})	Intrinsic (R_{cf})		Total (R_t)	Intrinsic (R_{cl})		$m^2 \cdot °C \cdot W^{-1}$	%
Bare Hot Plate	0.070		Nude manikin	0.10				
M3 - FRACU	0.099	0.029	CBEC - FRACU, IOTV	0.35	0.26	11.1	-0.012	-3.4
M2 - M4	0.086	0.016	EFRACU + CBUG (vents closed)	0.32	0.23	7.0	0.00093	0.3
M6-L3	0.089	0.020	CBCC Type B (small area), IOTV	0.30	0.22	9.1	-0.0024	-0.8
M5-L2	0.083	0.013	CBCC Type B (large area), IOTV	0.30	0.22	6.0	0.0044	1.4
Baseline	0.10	0.030	Baseline	0.32	0.23	12.9	-0.013	-4.1
Baseline - FRACU	0.12	0.048	Baseline - FRACU, IOTV	0.38	0.29	16.3	-0.030	-8.0
M1-L1	0.098	0.029	CBFRACU (vents closed)	0.32	0.23	12.3	-0.011	-3.5
M1-L1	0.098	0.029	CBCC Type A (vents closed)	0.31	0.23	12.5	-0.011	-3.6
FRACU*	0.087	0.017	FRACU no IOTV	0.25	0.16	10.5	---	---
FRACU*	0.087	0.017	FRACU with IOTV	0.31	0.22	7.8	---	---
Mean	0.094	0.025		0.32	0.23	10.6	-0.01	-2.7

*Fabric FRACU value was derived from the bare plate, baseline and baseline over FRACU values.

Table 7 Material Evaporative Resistance and Ensemble Evaporative Resistance in MOPP4

Fabric	Evaporative Resistance $m^2 \cdot Pa \cdot W^{-1}$		Ensemble MOPP4	Evaporative Resistance $m^2 \cdot Pa \cdot W^{-1}$		Fabric contribution %	Change if fabric was FRACU	
	Total (R_{eft})	Intrinsic (R_{ef})		Total (R_{et})	Intrinsic (R_{ecl})		$m^2 \cdot Pa \cdot W^{-1}$	%
Bare Hot Plate	5.82		Nude manikin	12.7				
M3 - FRACU	13.6	7.81	CBEC - FRACU, IOTV	69.6	59.0	13.2	-3.97	-5.7
M2 - M4	14.4	8.59	EFRACU + CBUG (vents closed)	67.4	56.8	15.1	-4.75	-7.1
M6-L3	13.1	7.24	CBCC Type B (small area), IOTV	64.7	54.1	13.4	-3.40	-5.2
M5-L2	15.3	9.47	CBCC Type B (large area), IOTV	64.7	54.1	17.5	-5.63	-8.7
Baseline	14.8	8.98	Baseline	62.2	51.7	17.4	-5.14	-8.3
Baseline - FRACU	18.6	12.8	Baseline - FRACU, IOTV	75.7	65.1	19.7	-8.98	-11.9
M1-L1	11.7	5.92	CBFRACU (vents closed)	60.6	50.0	11.9	-2.09	-3.4
M1-L1	11.7	5.92	CBCC Type A (vents closed)	60.4	49.8	11.9	-2.09	-3.5
FRACU*	9.66	3.84	FRACU no IOTV	37.7	27.1	14.2		
FRACU*	9.66	3.84	FRACU with IOTV	46.7	36.1	10.6		
Mean	13.3	7.44		60.96	50.37	14.5	-4.51	-6.7

*Fabric FRACU value was derived from the bare plate, baseline and baseline over FRACU values.

Table 8 Material Thermal Resistance and Ensemble Thermal Resistance in MOPP2

Fabric	**Thermal Resistance** m²·°C·W⁻¹		**Ensemble MOPP2**	**Thermal Resistance** m²·°C·W⁻¹		**Fabric contribution %**	**Change if fabric was FRACU fabric**	
	Total (R_{ct})	Intrinsic (R_{cf})		Total (R_t)	Intrinsic (R_{cl})		$m^2 \cdot °C \cdot W^{-1}$	%
Bare Hot Plate	0.070		Nude manikin	0.10				
M2 - M4	0.086	0.016	EFRACU - CBUG (vents open)	0.29	0.21	8.0	0.0060	0.3
M1-L1	0.10	0.029	CBFRACU (vents open)	0.29	0.20	14.0	-0.073	-3.9
M1-L1	0.10	0.029	CBCC Type A (vents open)	0.32**	0.23	12.3	-0.073	-3.5
FRACU*	0.087	0.017	FRACU with IOTV	0.28	0.20	8.9		
Mean	0.092	0.016		0.29	0.21	10.8	-0.01	-2.4

*Fabric FRACU value was derived from the bare plate, baseline and baseline over FRACU values.

Table 9 Material Evaporative Resistance and Ensemble Evaporative Resistance in MOPP2

Fabric	**Evaporative Resistance** m^{2}PaW^{-1}		**Ensemble MOPP2**	**Evaporative Resistance** m^{2}PaW^{-1}		**Fabric contribution %**	**Change if fabric was FRACU fabric**	
	Total (R_{eft})	Intrinsic (R_{ef})		Total (R_{et})	Intrinsic (R_{ecl})		m^{2}PaW^{-1}	%
Bare Hot Plate	5.82		Nude manikin	12.72				
M2- M4	14.4	8.59	EFRACU - CBUG (vents open)	57.62	47.02	18.3	-4.75	-8.2
M1 - L1	11.7	5.92	CBFRACU (vents open)	50.82	40.22	14.7	-2.09	-4.1
M1 - L1	11.7	5.92	CBCC Type A (vents open)	58.82	48.23	12.3	-2.09	-3.5
FRACU*	9.66	3.84	FRACU with IOTV	40.90	30.31	12.7		
Mean	11.9	6.07		52.04	41.45	14.49	-2.97	-5.3

*Fabric FRACU value was derived from the bare plate, baseline and baseline over FRACU values.

Figure 8 Relationship between material and ensemble resistance in MOPP4

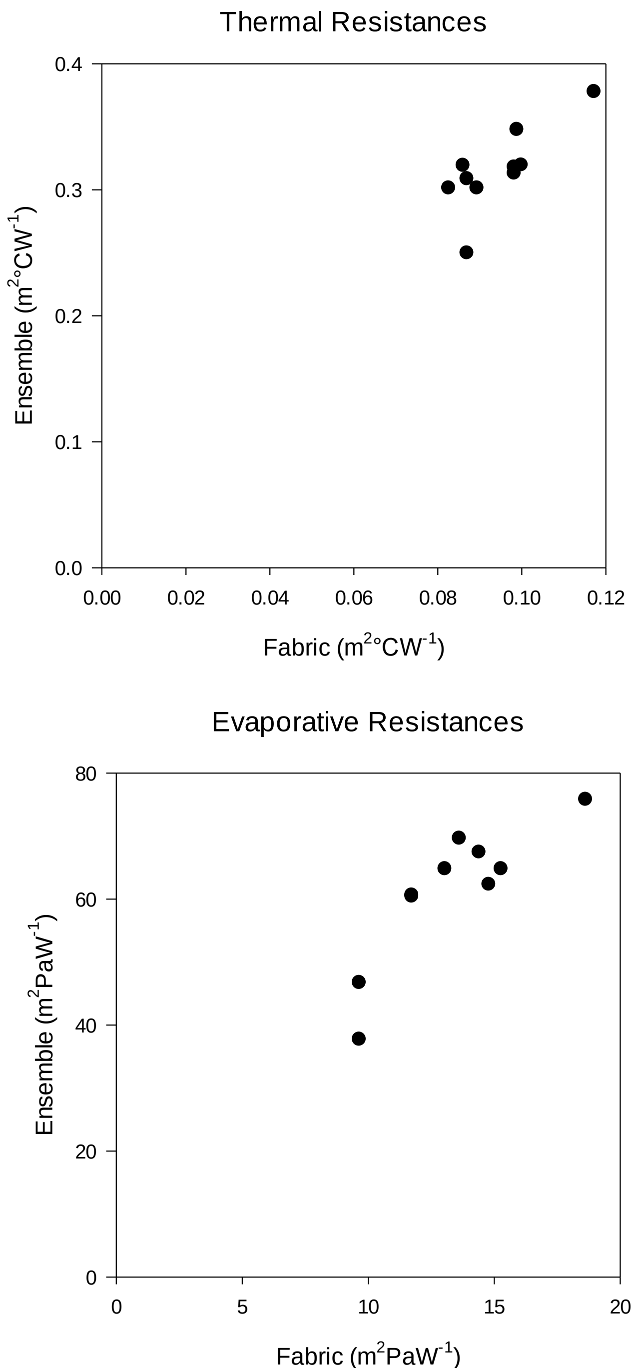
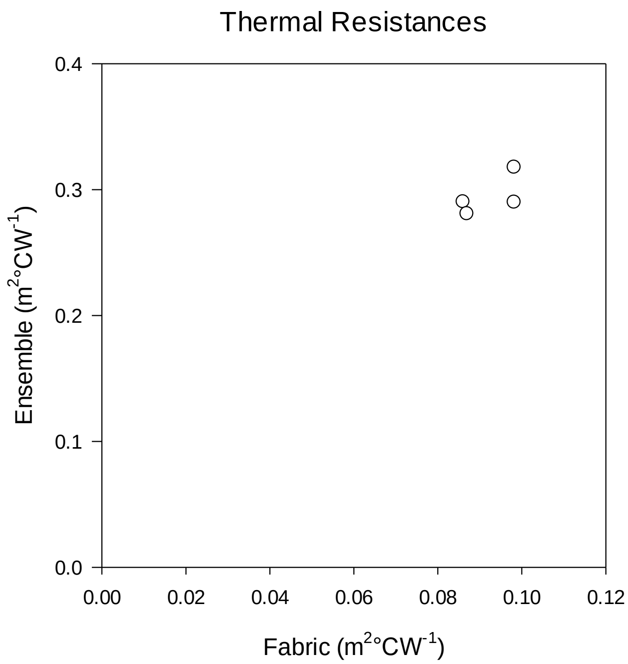
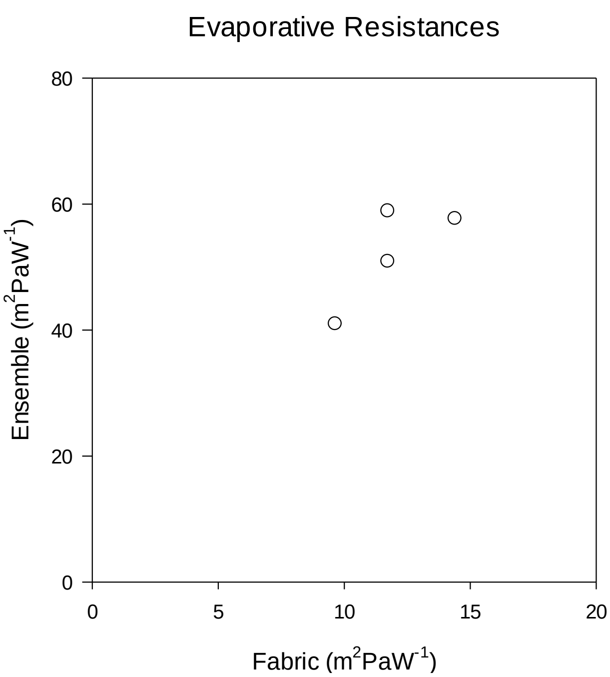


Figure 9 Relationship between material and ensemble resistance in MOPP2





EFFECT OF MATERIAL ON PREDICTED ENDURANCE TIME

Thermal and evaporative resistances are translated into human thermal responses through physiological modeling, enabling the research team to consider effects of different metabolic rates and environmental conditions. Translating the biophysics properties of ensembles into physiological responses will enable materiel developers to understand how the properties of the different ensembles will impact the Soldiers wearing the ensembles. The HSDA model was used to predict endurance times at a moderate metabolic rate of 400 W under following environmental conditions:

Table 10 Environmental Conditions

Environment	Air Temp. (°C)	RH (%)	Air Velocity ($m\ s^{-1}$)	Solar
Temperate	20	50	2	sunny
Hawaii	26	55	9	sunny
Jungle	30	75	2	sunny
Desert	40	20	2	sunny

Fabric thermal properties and predicted endurance times are shown in **Error! Reference source not found.** to Table 14 and Figure 10 to Figure 13. Endurance times are affected by fabric thermal and evaporative resistances, but the effects are dependent on environmental conditions. As the results show, the effects of evaporative resistance are more apparent than that of thermal resistance. With MOPP4 ensembles, the endurance times increase as fabric evaporative resistance is reduced from 18.8 to 9.7 $m^2{\cdot}P_a{\cdot}W^{-1}$ in the Temperate condition. Even with the same fabric thermal and/or evaporative resistance, the endurance times are not necessarily the same, as factors other than fabric can play a role in thermal and evaporative resistance. Those factors include the ensemble design, and the different layers and components included in the ensembles. For example, the differences in endurance times with the two FRACU ensembles in the Jungle and Desert condition are caused by the body armor (IOTV). The endurance time differences between the MOPP4 and MOPP2 ensembles are caused by the open vent (excluding FRACU 2010 full) and additional configuration changes (e.g., hood down, jacket open) at the lower protection level. With MOPP2 ensembles, effects of fabric on endurance times are only evident in the Jungle and Desert conditions.

Table 11 Material Thermal Resistance and Predicted Endurance Time with Ensemble in MOPP4

Fabric	Total Thermal Resistance, R_{ct}		Ensemble	Predicted Endurance Time (min)			
	$m^2 \cdot °C \cdot W^{-1}$	clo		Desert	Hawaii	Temperate	Jungle
M3 - FRACU	0.099	0.64	CBEC - FRACU MOPP4 Full*	93	204	188	94
M2 - M4	0.086	0.56	CBUG - EFRACU MOPP4 Full*	93	197	209	95
M6 - L3	0.089	0.58	CBCC-B MOPP4 Full*	91	243	225	95
Baseline	0.10	0.64	Baseline MOPP4 Full*	97	265	238	97
Baseline - FRACU	0.12	0.76	Baseline - FRACU MOPP4 Full*	93	188	169	92
Baseline - FRACU	0.12	0.76	Baseline - FRACU Full* MOPP4**	101	286	205	100
Baseline - FRACU	0.12	0.76	Baseline - FRACU MOPP4**	103	298	221	99
M1 - L1	0.098	0.63	CBFRACU MOPP4 Full*	95	269	240	97
M1 - L1	0.098	0.63	CBCC-A MOPP4 Full*	96	300	257	98
M5 - L2	0.083	0.53	CBCC-B MOPP4 Full*	91	243	225	95
FRACU	0.09	0.56	FRACU MOPP4**	171	300	300	159
FRACU	0.09	0.56	FRACU Full* MOPP4**	132	300	300	124

*Full indicates full combat load including IOTV and helmet

**Thermal manikin data taken from (26)

Table 12 Material Evaporative Resistance and Predicted Endurance Time with Ensemble in MOPP4

Fabric	Total Evaporative Resistance, R_{eft}		Ensemble	Predicted Endurance Time (min)			
	$m^2 \cdot Pa \cdot W^{-1}$	i_m		Desert	Hawaii	Temperate	Jungle
M3 - FRACU	13.6		CBEC - FRACU MOPP4 Full*	93	204	188	94
M2 - M4	14.4	0.44	CBUG - EFRACU MOPP4 Full*	93	197	209	95
M6 - L3	13.1	0.36	CBCC-B MOPP4 Full*	91	243	225	95
Baseline	14.8	0.42	Baseline MOPP4 Full*	97	265	238	97
Baseline - FRACU	18.6	0.41	Baseline - FRACU MOPP4 Full*	93	188	169	92
Baseline - FRACU	18.6	0.38	Baseline - FRACU Full* MOPP4**	101	286	205	100
Baseline - FRACU	18.6	0.38	Baseline - FRACU MOPP4**	103	298	221	99
M1 - L1	11.7	0.38	CBFRACU MOPP4 Full*	95	269	240	97
M1 - L1	11.7	0.51	CBCC-A MOPP4 Full*	96	300	257	98
M5 - L2	15.3	0.51	CBCC-B MOPP4 Full*	91	243	225	95
FRACU	9.66	0.33	FRACU MOPP4**	171	300	300	159
FRACU	9.66	0.55	FRACU Full* MOPP4**	132	300	300	124

*Full indicates full combat load including IOTV and helmet

**Thermal manikin data taken from (26)

Table 13 Material Thermal Resistance and Predicted Endurance Time with Ensemble in MOPP2

Fabric	Total Thermal Resistance, R_{ct}		Ensemble MOPP2	Predicted Endurance Time (min)			
	$m^2 \cdot °C \cdot W^{-1}$	clo		Desert	Hawaii	Temperate	Jungle
M2 - M4	0.099	0.56	CBUG - EFRACU MOPP2 Full*	128	300	300	124
Baseline - FRACU	0.12	0.76	Baseline Full* MOPP2**	116	300	300	113
M1 - L1	0.098	0.63	CBFRACU MOPP2 Full*	116	300	300	116
M1 - L1	0.098	0.63	CBCC-A MOPP2 Full*	114	300	300	111
FRACU	0.094	0.56	FRACU Full* MOPP2**	169	300	300	153

Table 14 Material Evaporative Resistances and Predicted Endurance Time with Ensemble in MOPP2

Fabric	Total Evaporative Resistance, R_{eft}		Ensemble MOPP2	Predicted Endurance Time (min)			
	$m^2 \cdot Pa \cdot W^{-1}$	i_m		Desert	Hawaii	Temperate	Jungle
M2 - M4	14.4	0.36	CBUG - EFRACU MOPP2 Full*	128	300	300	124
Baseline - FRACU	18.6	0.38	Baseline Full* MOPP2**	116	300	300	113
M1 - L1	11.7	0.51	CBFRACU MOPP2 Full*	116	300	300	116
M1 - L1	11.7	0.51	CBCC-A MOPP2 Full*	114	300	300	111
FRACU	9.66	0.55	FRACU Full* MOPP2**	169	300	300	153

*Full indicates full combat load including IOTV and helmet

**Thermal manikin data taken from (26)

Figure 10 Effect of material thermal resistance on predicted endurance times for MOPP4 ensembles at Temperate, Hawaii, Jungle and Desert conditions

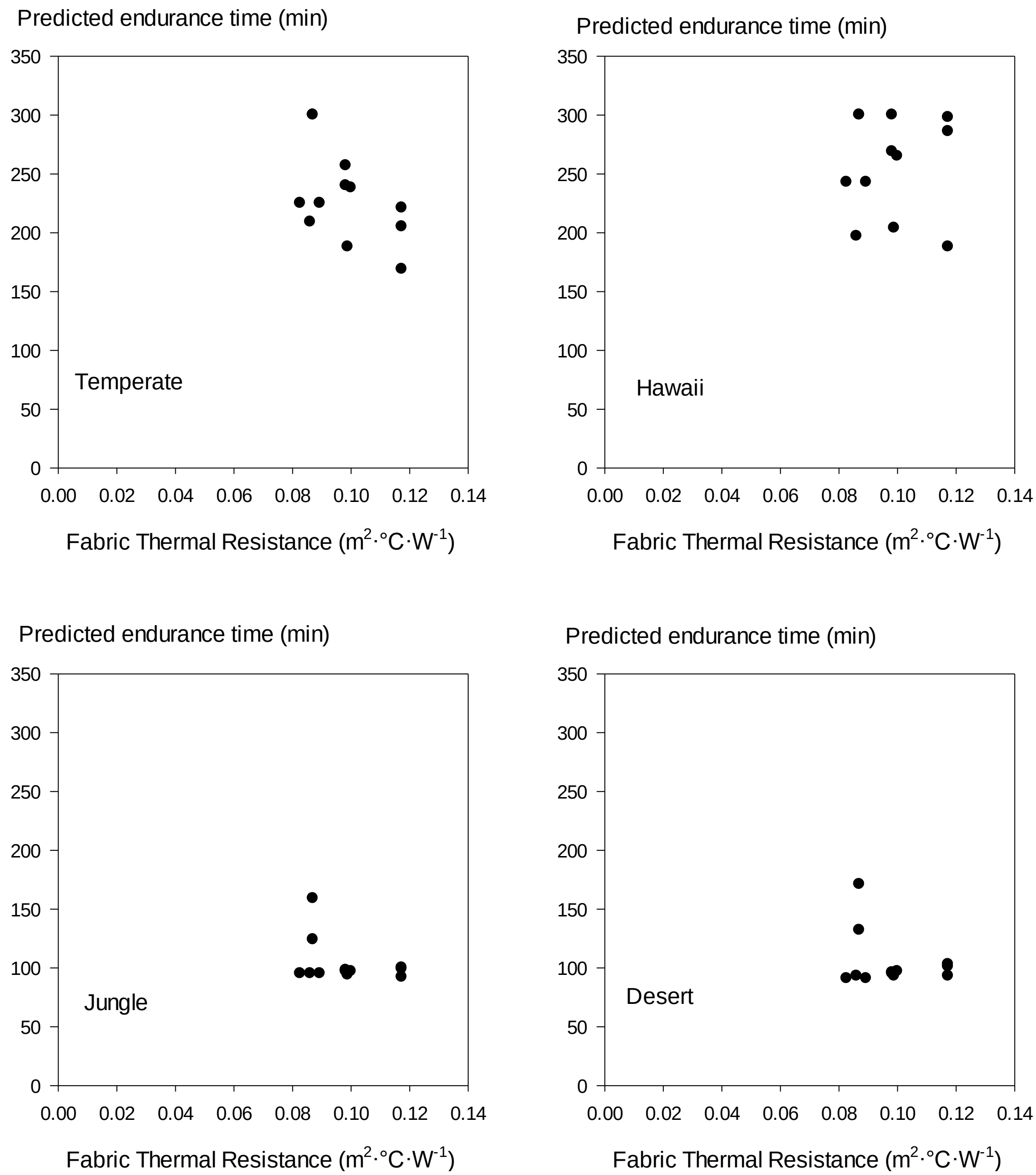


Figure 11 Effects of material evaporative resistance on predicted endurance times for MOPP4 ensembles at Temperate, Hawaii, Jungle and Desert conditions

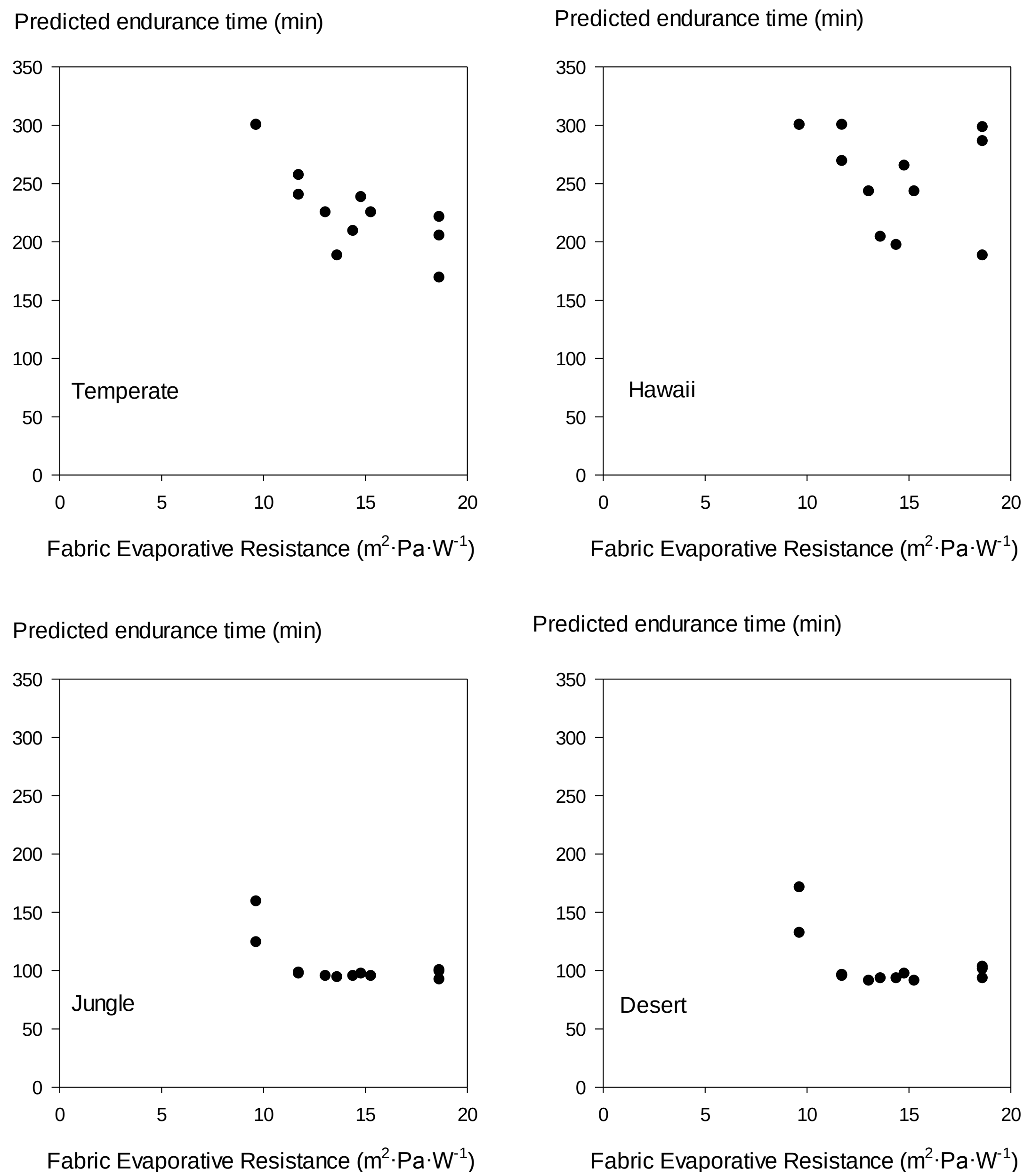


Figure 12 Effects of material thermal resistance on predicted endurance times for MOPP2 ensembles at Temperate, Hawaii, Jungle and Desert conditions

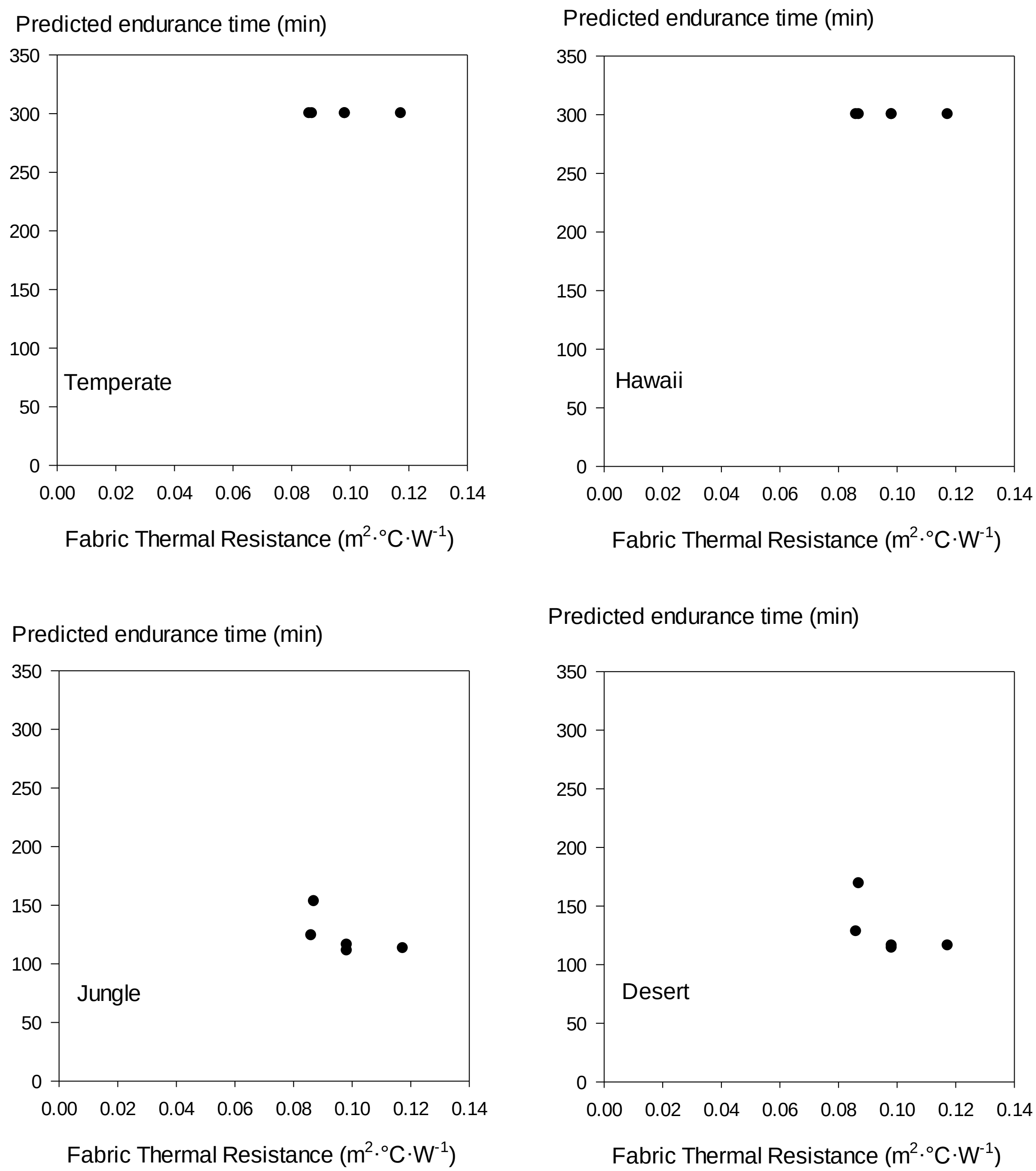
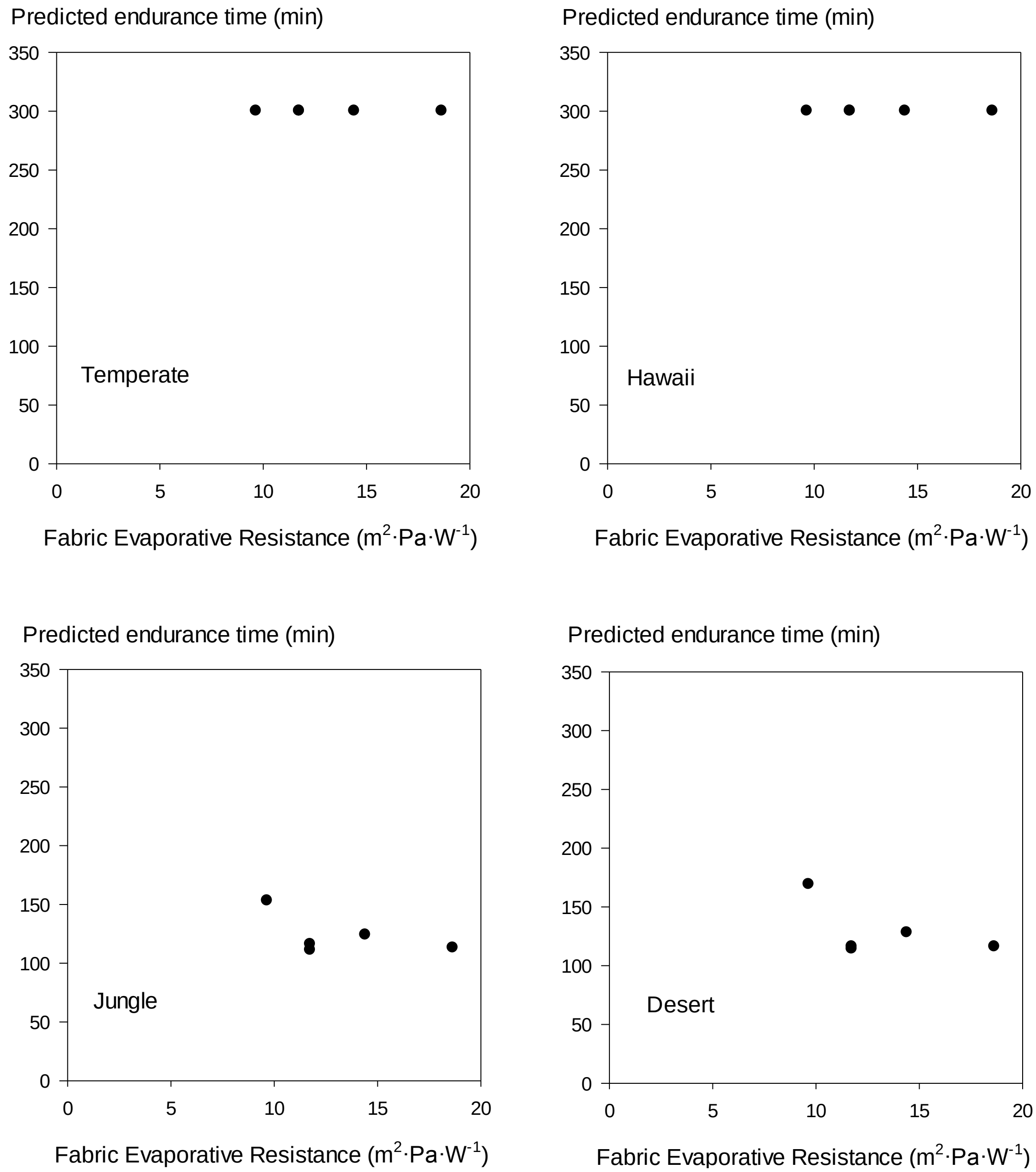


Figure 13 Effects of material evaporative resistance on predicted endurance times for MOPP2 ensembles at Temperate, Hawaii, Jungle and Desert conditions



DISCUSSION

This report is the first systematic analysis of (A) the relationship between material thermal properties and ensemble thermal properties, and (B) the relationship between material thermal properties and predicted endurance times relative to heat strain in soldiers wearing in CB protective clothing. The analysis shows that fabrics contribute only ~10.6% to the total thermal resistance and ~14.7% to the total evaporative resistance of these fourteen ensembles in the report. If fabrics were replaced by FRACU fabric, the thermal and evaporative resistances of the fourteen ensembles would be reduced by 2.7% and 6.7% respectively. Predicted endurance times at a 400 W metabolic rate are affected by material thermal and evaporative resistances, but the effects are dependent on environmental conditions. Thus, an improvement in fabric thermal properties may or may not result in any differences in observed physiological responses during human studies. Furthermore, one of the best performing fabrics, e.g., M1-L1, has similar thermal properties to the FRACU fabric (~3.5%). Assuming that thermal properties of a CB protective fabric will not exceed the thermal properties of the FRACU fabric, then improving fabric thermal properties would only result in a ~3.5% improvement in ensemble thermal properties. Therefore, it is incumbent on the research and development team to explore other options on a material level to maximize the potential to reduce thermal burden, such as novel materials that actively transport water vapor away from the body or actively reduce temperature. Another approach is to reduce thermal burden at the system level, such as garment design or weight reduction.

The resistance values of CB protective fabrics contribute only a relatively small percentage to the overall ensemble resistance values. The remaining ensemble resistance is due to additional layers or components added to the ensemble and air gaps that exist between the skin and the ensemble external surface. According to Eq. 11 and 12, any additional layers or components in the ensemble will increase the thermal and evaporative resistance of the ensemble. The evaporative resistance of FRACU with and without the IOTV (Table 7) shows that IOTV increases the evaporative resistance by 9 $m^2 \cdot Pa \cdot W^{-1}$, which is more than two times the intrinsic evaporative resistance of the FRACU fabric, which is 3.8 $m^2 \cdot Pa \cdot W^{-1}$. In other words, the evaporative resistance of FRACU MOPP4 ensemble increases by 24% when the IOTV is added onto the ensemble. Therefore, the resulting thermal burden is the result of the combined effect of every layer or component in the ensemble. It is not uncommon for specific configurations of an ensemble to be tested with various layers or components (see Table 4 and Table 5 for examples). While this approach has been effective in supporting PPE research and development, it may provide more information on the contribution of specific individual layers or components to the overall thermal and evaporative resistances if a more systematic approach of testing individual layers as well as selected configurations were adopted. It is also difficult to use the results to compare ensemble thermal performance, see Figure 10 and Figure 11 for example, as the differences may be caused by the differences in the layers or components rather than the clothing itself. Thus, it is recommended that manikin testing should include a baseline configuration (a simple base layer as a control – e.g., CB garment in MOPP4 without ballistic protection, see Figure 3 to Figure 7).

USARIEM has recently developed a stepwise manikin testing approach to determine the contribution of major layers or components (1). This approach consists of the following steps: (A) evaluate the threats and requirements for PPE systems and identify different configurations which will provide options for different levels of protection within the PPE system; (B) test those configurations on a thermal manikin; (C) analyze the contributions of the specific layers to the overall thermal and evaporative resistance. Quantifying the fractional contribution of each major layer or component will help designers or decision makers understand the contribution of different ensemble elements to the thermal burden and to select appropriate strategies to reduce thermal burden.

The clothing research and development community has been interested in approaches that can predict ensemble thermal properties at the system level from fabric thermal properties measured at the swatch level. This information will help clothing designers or materiel developers to understand, during the early stage of PPE research and development, the potential changes that a new fabric may bring. A heat and mass transfer model was developed to predict ensemble properties from fabric properties and ensemble geometry (i.e., air gaps) (27, 28). Air gaps can be determined from whole body scans (29). At present, this approach works only for one-layer systems, but has potential for improvement. Eq. 15 and 16 present a simple approach to estimate changes of ensemble thermal and evaporative resistance if the current fabric is replaced by a new fabric. The conditions on the use of these equations are strict: the clothing design and configuration must not be changed, and only the fabric can be replaced. For example, the following changes would occur if the M1-L1 fabric was substituted with the FRACU fabric (see Table 7 for evaporative resistance values). The evaporative resistances of CBFRACU and CBCC Type A ensembles would only be reduced by 3.5% if M1-L1 was replaced by FRACU fabric. This analytic approach helps materiel developers estimate potential effects of the fabric on the prototype ensemble.

It is clear from Figure 10 and Figure 11 that the effects of fabric on predicted endurance times are dependent on the environmental conditions. For example, with MOPP4 ensembles (excluding FRACU ensembles), fabric evaporative resistance ranges from 11.7 to 18.6 $m^2 \cdot P_a \cdot W^{-1}$. The corresponding predicted endurance times range from 169 to 300 min in Temperate conditions and only from 94 to 159 min in Jungle conditions. For the MOPP2 ensembles, the predicted endurance times are the same in both Hawaii and Temperate conditions, but are slightly different in Desert and Jungle conditions. These findings suggest that the effects of improved fabric thermal properties on physiology responses, e.g., endurance times, may only be observed under certain environmental conditions.

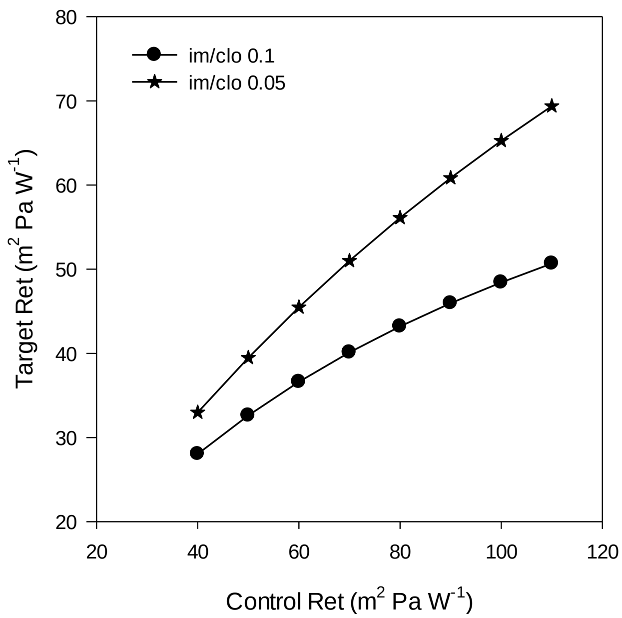
In addition, predicted endurance times are influenced by metabolic rates (1, 16-18). For the HSDA simulation, the metabolic rate was set at a constant rate of 400 W. It is a reasonable expectation that the predicted endurance times would be different if the metabolic rates were different. The literature shows that physiological responses of subjects wearing PPE were influenced by work rates and environmental conditions (30-33). When human studies are used to evaluate PPE performance, the differences in measured physiological responses are often too small and/or variable to justify rank ordering the candidate chemical protective ensembles (33). Therefore, conditions and experimental designs for human studies (e.g., environmental conditions and activity levels) should be carefully selected to ensure there will be a wide enough range in the physiology responses to capture the small differences in fabric effects as well as differences among configurations. The manikin testing and modeling approach can help researcher select appropriate experimental conditions.

The IOTV clearly affects the thermal burden. The FRACU data with and without the IOTV in Table 6 and Table 7 show that the IOTV added a thermal resistance of ~0.06 $m^2 \cdot °C \cdot W^{-1}$ and an evaporative resistance of ~9 $m^2 \cdot P_a \cdot W^{-1}$ to the ensembles. The addition translated into a 35 to 39 minute difference in predicted endurance times in Jungle and Desert conditions (**Error! Reference source not found.** and Table 12). However, the HSDA simulation was based on a fixed metabolic rate of 400 W and did not take into account any increase in metabolic rates associated with carrying the IOTV mass. Furthermore, the IOTV covers the torso area which represents about 30% of the body surface area (34). The sweat rate in this body region is about 60% higher than the body average (35). Therefore, the IOTV exacerbates the heat strain in PPE by increasing thermal and evaporative resistance, by increasing metabolic rate, and by reducing evaporative heat loss by covering an area associated with a high rate of sweat production and evaporation. The stepwise manikin testing and modeling approach can be used to quantify the impact of the IOTV on endurance times accounting for effects of increases in thermal resistance, evaporative resistance and mass (e.g., load carried)(1).

Mass was not included in the data nor in this analysis, but it plays a critical role in exacerbating heat strain in PPE. It is expected that weight reduction of the five new ensembles in Table 2 would result in longer endurance times. The mass of a basic FRACU ensemble is about 4.5 kg, and the weight gradually increases to 38 kg after chemical protective clothing, combat load equipment, body armor, etc., were added to the ensemble. As a result, metabolic rates increase from 300 W to 430 W during walking at a pace of 1.22 $m \cdot s^{-1}$ and 500 W to 706 W during walking at a pace of 1.76 $m \cdot s^{-1}$. When wearing PPE, an increase in metabolic rate increases heat production, heat storage, and thus reduces endurance times. The effects of PPE mass on heat strain are of a similar magnitude to the effects of increased thermal and evaporative resistances associated with PPE (1). In addition, the increase in metabolic rates when wearing PPE has been attributed to both added mass and other less well defined factors such as the hobbling effects of bulky PPE ensemble, etc. (3, 36, 37). In one study, two military PPE systems have similar masses, but the observed increases in metabolic rate differed by 5% when performing the same task (3). In cases like this, it would be useful to identify these factors (e.g., the effects of compression and air gaps between clothing and equipment layers on the heat exchange through the garment system, hobbling, distribution of weights) to see if it is possible to reduce the metabolic heat production associated with these factors.

Figure 2 shows that evaporative heat loss usually becomes the dominant heat loss avenue as environmental temperatures rise. Therefore, the predicted endurance times and other related human physiology responses are more sensitive to evaporative resistance than thermal resistance in warm and hot environments. A recent human study demonstrated that the fabric evaporative resistance is the most highly correlated factor to predict thermal strain in four chemical protective coveralls (38). Traditionally, in order to justify a study involving human volunteers, the difference between a control and a prototype ensemble must be greater than or equal to a threshold value of 0.1 i_m/clo. Otherwise, it is unlikely that a significantly different physiological effect will be observed. Eq. 8 can be used to determine the evaporative resistance of a prototype ensemble that will meet this criterion, as show in Figure 14. Most of ensembles in Table 7 and Table 9 have evaporative resistances from 60 to 70 $m^2 \cdot P_a \cdot W^{-1}$. Therefore, in order to meet the 0.1 i_m/clo threshold value, a control ensemble with an evaporative resistance of 65 $m^2 \cdot P_a \cdot W^{-1}$, the evaporative resistance of a prototype ensemble that meets the 0.1 threshold should be 38 $m^2 \cdot P_a \cdot W^{-1}$. This means that the prototype ensemble would need to be, in terms of an evaporative resistance, as good as the FRACU without IOTV, which is challenging to achieve for a PPE ensemble. Thus it is necessary to explore more options to enhance convective evaporative heat loss, such as materials with high porosity (30, 39) or water vapor transport.

Figure 14 Target evaporative resistances to reach im/clo 0.1 and 0.05 threshold as a function of the baseline evaporative resistances, estimated using Eq.8



This analysis was based on the data provided. The data had been collected and compiled for analysis over a period of several years. It is possible that over time, some variability was introduced into the data during the collection, processing or compilation steps. The ensembles tested included chemical protective clothing with various layers or components (see Table 4, Table 5). Some differences in the overall thermal and evaporative resistances are due to differences in the layers or components. Therefore, a degree of caution may be required if the results of this analysis are compared to other similar analyses.

CONCLUSIONS

This report analyzed the relationships among thermal properties of eight fabrics at the swatch level, thermal properties of fourteen multi-layer ensembles at the system level, and predicted endurance times for four typical operational conditions. Fabrics contributed only ~10.6% of the thermal resistances and ~14.5% of the evaporative resistances to the total resistances of these fourteen multi-layer ensembles in the report. If fabric thermal properties were the same as FRACU fabric, the thermal and evaporative resistances of the fourteen ensembles would reduce by only 2.7% and 6.7% respectively. Therefore, improved thermal properties at the swatch level will result in either a slight change or no difference in thermal properties at the system level. Thermal burden is a result of the combined effects of every layer or component in the ensemble. Each additional layer or component increases the overall thermal and evaporative resistances of the ensembles. It is incumbent on the research and development team to explore all possible options both on a material level and at the system level to maximize the potential to reduce thermal burden.

Predicted endurance times at 400 W metabolic rate are affected by fabric thermal and evaporative resistances, but the effects are dependent on environmental conditions. Thus, an improvement in fabric thermal properties may or may not result in any differences in observed physiological responses during human studies.

ITOV increases thermal burden by increasing thermal and evaporative resistances of ensembles, increasing metabolic cost of locomotion by increasing mass carried, and by impeding sweat evaporation from the torso.

RECOMMENDATIONS

Continue to improve the thermal performance of individual protective fabrics but increase the efforts to identify ways to modify and manipulate complete ensembles to reduce the thermal burden on Soldiers.

Analytically, separate complete ensemble systems into two subsystems: a chemical protection subsystem and a combat subsystem (e.g. a CB protective garment in MOPP4 measured both with and without ballistic protection). Quantify the contribution of each subsystem to the total thermal burden, and identify underlying mechanisms determining total thermal burden (e.g., increases in thermal and evaporative resistance, increases in metabolic rate associated with added mass carried, etc.).

Establish protocol standards to collect and record the thermal properties at the swatch level and at the system level. Test results should include current bare SGHP tests and nude manikin tests as controls. In addition to ensemble tests (configurations with different layers/components), it may be useful to include tests of a baseline configuration (e.g. the base layer of CB protective without additional layers or components) as a control. This will facilitate post analysis and comparison of data collected in different studies.

Establish baseline database for whole ensemble systems that includes system characteristics (e.g., individual system components, typical configurations, weight of each item), the biophysical properties (thermal resistance, evaporative resistance) of each layer or component (e.g., IOTV, CB mask, gloves, over-boots, etc.), and the predicted physiological responses (e.g., thermal strain for humans wearing and working in PPE).

Use existing algorithms and models to predict the effects of PPE mass on metabolic heat production and heat strain, and guide efforts to reduce thermal burden.

Analyze the heat and mass transfer mechanisms (convection, radiation, diffusion, etc.) from the skin, through the ensembles, to the environment. Investigate heat and vapor transfer mechanisms across layer-to-layer and skin-to-layer air gaps. Understanding how intra-ensemble air gaps influence total ensemble thermal and evaporative resistances may lead to new ensemble designs that reduce the thermal burden.

Expedite early-stage ensemble R&D by improving our understanding of the relationships among thermal properties measured at the swatch level, thermal properties at the system level, and predicted or observed human physiology responses.

Use predictive modeling to inform decisions regarding the design of experiments with human test volunteers. This will help ensure that the environmental conditions and physical activity levels selected are wide enough to capture the differences among systems and configurations.

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