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BIOPHYSICAL PROPERTIES OF FIVE COLD WEATHER CLOTHING SYSTEMS AND THE PREDICTED REGIONAL PROPERTIES OF ENSEMBLES

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United States Army
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14. ABSTRACT
Thermal and evaporative resistance measurements from sweating thermal manikins were collected for five cold-weather ensemble systems from the U.S. Army, U.S. Marine Corps, U.S. Special Forces, Canadian Armed Forces, and Norwegian Armed Forces, a total of 60 garments and 34 ensemble configurations. All clothing data was separated into six regions for the head, torso, arm, hand, leg, and foot. Linear regression analysis generated equations for the torso, arm, and leg regions to predict regional ensemble resistances from the sum of regional garment resistances. The regional data presented in this report, as opposed to whole-body data, provides a new perspective on clothing properties and are critical to materiel developers for the optimization of cold-weather ensemble design. Newly created equations improve accuracy for predictions of ensemble resistances for the torso, arm, and leg body regions.

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EXECUTIVE SUMMARY

Introduction: This report describes the biophysical properties of five cold-weather ensemble systems from the U.S. Army, U.S. Marine Corps, U.S. Special Forces, Canadian Armed Forces, and Norwegian Armed Forces. Thermal and evaporative resistance measurements were obtained using a sweating thermal manikin. This work shows newly collected cold-weather clothing data, and compiles previously collected cold-weather clothing data computed for cold thermoregulatory modeling. Data analysis of all compiled measurements allowed for development of equations to predict ensemble resistances from the sum of individual garment resistances. These equations are necessary to improve the accuracy of underlying clothing property calculations in the Cold Weather Ensemble Decision Aid (CoWEDA), a user-friendly software application that implements a cold-weather thermoregulatory model. **Methods:** Thermal resistance and evaporative resistance measurements were collected for each individual garment and selected configurations of five cold-weather clothing systems, 60 total garments and 34 ensemble configurations. Intrinsic regional resistances for the head, torso, arm, hand, leg, and foot regions were calculated for each garment and ensemble. Plots of the torso, arm, and leg region data for both thermal and evaporative resistances were created and linear regression analysis used to generate equations that predict ensemble resistances from the sum of individual garment resistances. **Results:** Intrinsic thermal (R_{cl}, clo) and evaporative resistances (R_{ecl}, m^2Pa/W) of garments range from 0.07–7.03 clo and 0.48–154 m^2Pa/W for the torso, 0.00–5.15 clo and 0.00–168 m^2Pa/W for the arm, and 0.00–2.60 clo and 0.00–128 m^2Pa/W for the leg region. Intrinsic thermal and evaporative resistances of ensembles range from 1.33–9.23 clo and 24.9–314 m^2Pa/W for the torso, 0.93–5.95 clo and 21.7–179 m^2Pa/W for the arm, and 0.86–4.48 clo and 11.6 –180 m^2Pa/W for the leg region. The R^2 of the linear regression equations derived from the relationship between measured ensemble thermal resistances and the sum of garment thermal resistances are 0.655, 0.924, 0.939, and 0.854, for whole-body, torso, arm, and leg, respectively. The R^2 of the linear regression equations derived from the relationship between measured ensemble evaporative resistances and the sum of garment evaporative resistances are 0.510, 0.572, 0.851, and 0.864, respectively. **Discussion:** Low R^2 value of 0.572 for the plot of R_{ecl} torso region may be explained by excessive water being trapped inside the heavy clothing. More work needs to be completed to determine if this anomaly continues. Future work may also include conducting similar in-depth analyses to improve prediction equations of the head, hand, and foot regions. **Conclusion:** This report details the biophysical properties of thermal resistance and evaporative resistance for five cold-weather clothing systems. The measurements for ensembles and garments, i.e., individual clothing items, are reported. Additionally, values for the whole-body as well as smaller regions are presented. Finally, equations were derived to predict the regional thermal and evaporative resistances of ensembles from the measurements of individual garments. The regional data presented in this report, as opposed to whole-body data, provides a new perspective on clothing properties and are critical to materiel developers for the optimization of cold-weather ensemble design. Newly created equations will improve accuracy for predictions of ensemble resistances for the torso, arm, and leg body regions.

INTRODUCTION

Exposure to extreme cold-weather environments can lead to life-threatening injuries such as hypothermia and life-altering injuries such as frostbite. Risk of these injuries can be mitigated by wearing appropriate cold-weather clothing and equipment. Risks can be more proactively mitigated when detailed knowledge of the capabilities and limitations of specific clothing across environmental conditions are known [1-3]. USARIEM has a long history of providing guidance on appropriate clothing to wear or pack on a mission, as well as recommending exposure times for extreme environments [4]. A current limitation is an insufficient database and knowledge about the properties of extreme cold weather clothing items and systems. Historically, clothing items and systems were assigned single, whole-body insulation (i.e., thermal resistance) and vapor permeability (i.e., evaporative resistance) values and whereas today it is recognized that more accurate predictions of exposure tolerance time can be made if clothing biophysical properties are made at discrete body locations [5-7].

This report provides a comprehensive breakdown of the biophysical properties i.e., thermal and evaporative resistances, for all the individual garments composing five military clothing systems and selected ensemble configurations of those clothing systems. Additionally, equations were derived to predict the thermal and evaporative resistances of ensembles at specific regions of the body and these are provided as well. The five cold-weather clothing systems that were evaluated are the Military Alpine Recce System developed for the U.S. Special Operations Forces (SOF), the Canadian Armed Forces (CAF) cold-weather clothing system, the Norwegian Armed Forces (NAF) cold-weather clothing system, the U.S. Army's Generation III Extended Cold Weather Clothing System (ECWCS), and the U.S. Marine Corps (USMC) cold-weather clothing system. The biophysical testing results of the SOF system are introduced in this report. Certain aspects of the biophysical properties of the CAF, NAF, and ECWCS systems have been included in a separate report [8], these did not include regional values for the six body regions necessary for accurate cold-weather modeling. The USMC cold-weather clothing system has been completely described in a previous report, and is presented here for convenient reference and completeness [9].

Prediction equations developed in this report use thermal and evaporative resistances of the individual garments to predict the thermal and evaporative resistances of full ensembles. This proposed method aims to create separate equations for six body regions: head, torso, arm, hand, leg, and foot, with this report focusing on equations for the torso, arm, and leg regions. These equations are important to the underlying functions and accurate predictions in the Cold Weather Ensemble Decision Aid (CoWEDA), a software application that utilizes USARIEM's six cylinder thermoregulatory model (SCTM) [5, 6] to predict regional body temperatures and cold tolerance times before hypothermia or distal frostbite injury [7, 10]. CoWEDA is intended for use by Soldiers in the field, e.g., logisticians and commanders, to determine the required clothing during mission planning. The equations currently used for CoWEDA clothing ensemble prediction were based on the USMC and ECWCS systems and are currently unpublished. The data generated in this effort should enable improved equations, in part, by adding data from three more systems (SOF, CAF, and NAF).

METHODS

MATERIALS

Five cold-weather clothing systems were analyzed and compiled into this report. The result is a detailed evaluation of 60 garments and 34 selected ensemble configurations. A breakdown of how those garments and ensembles are distributed amongst the five clothing systems is shown in Table 1. In many cases, there are some minor variations in the ensemble or garment test configurations, such as the hood up (worn over the head) and the hood down. The count in Table 1 does not account for these minor variations. For example, if a jacket with a hood was tested in both hood up and hood down configurations, the jacket was counted as a single garment tested in Table 1. All garments evaluated were size medium regular to ensure proper fit on the thermal manikin. Pictures of all the garments are located in Appendix A.

Table 1. Number of ensembles and garments tested for each clothing system

System name	n Garments	n Ensembles
SOF	15	6
CAF	9	6
NAF	11	5
ECWCS	12	9
USMC	13	8

Ensemble configurations were generally selected by project managers and Subject Matter Experts (SME) of each clothing system and were based on typical or recommended configurations that are worn in the field. Matrices that illustrate which garments were included in each ensemble configuration are shown in Figures 1-5 for the SOF, CAF, NAF, ECWCS, and USMC clothing systems, respectively. In these figures, the number associated with each ensemble configuration is listed in the top row (number value is arbitrary), and individual garments are listed in the leftmost column. Colored-in cells indicate that the garment is included in the ensemble configuration.

Figure 1. Special Operations Forces Ensemble Matrix

SOF	Ensemble					
	1	2	3	4	5	6
LW Long Sleeve Crew Shirt					■	■
LW Boxer Briefs					■	■
MW Quarter Zip	■	■	■	■		■
MW Long John	■	■	■	■		■
Mixed Range Jacket		■	■		■	
Mixed Range Pants		■	■		■	
Pneumo Fuse Top	■					■
Pneumo Fuse Pants	■			■		■
Nano Air Hoody				■	■	
Nano Air Pants					■	
DAS Jacket	■	■	■	■		■
DAS Pants	■	■	■	■		■
Helo Parka			■			

Figure 2. Canadian Armed Forces Ensemble Matrix

CAF	Ensemble					
	1	2	3	4	5	6
Thermal Undershirt	■	■	■	■	■	■
Long Johns	■	■	■	■	■	■
CADPAT Fleece Jacket			■	■	■	■
CADPAT Fleece Trousers			■	■	■	■
CADPAT ICE Jacket	■				■	
CADPAT ICE Trousers	■				■	
CADPAT IECS Parka		■	■			
CADPAT IECS Bib Pants		■	■	■		
Snow Mantra Winter Parka				■		■

Figure 3. Norwegian Armed Forces Ensemble Matrix

NAF	Ensemble				
	1	2	3	4	5
Net Undershirt	■	■	■	■	■
Net Underwear	■	■	■	■	■
Wool Terry Cloth Undershirt	■	■	■	■	■
Wool Terry Cloth Underwear	■	■	■	■	■
Cotton Field Shirt		■	■	■	■
M/02 Membrane Field Jacket	■	■			
M/02 Membrane Field Trouser	■	■			
M/97 Camouflage Jacket (white)	■		■		■
M/97 Camouflage Trouser (white)	■		■		■
Cold Weather Jacket				■	■
Cold Weather Trousers				■	■

Figure 4. U.S. Army's Generation III Extended Cold Weather Clothing System Ensemble Matrix

ECWCS Gen III	Ensemble								
	1	2	3	4	5	6	7	8	9
Lightweight Undershirt	■	■	■	■			■	■	■
Lightweight Drawers	■	■	■	■			■	■	■
Midweight Shirt	■	■	■	■	■	■			
Midweight Drawers	■	■	■	■	■	■			
Fleece Jacket		■	■	■					■
Soft Shell Jacket			■	■	■	■	■		
Soft Shell Trouser			■	■	■	■	■		
Extreme Cold/Wet Weather Jacket								■	■
Extreme Cold/Wet Weather Trouser								■	■
Extreme Cold Weather Parka				■		■			
Extreme Cold Weather Trouser				■					

Figure 5. U.S. Marine Corps Ensemble Matrix

USMC	Ensemble							
	1	2	3	4	5	6	7	8
Silkweight Undershirt	■	■	■	■		■	■	■
Silkweight Drawers	■	■	■	■		■	■	■
Grid Fleece Pullover			■	■	■			
Grid Fleece Drawers			■	■	■			
FR Combat Ensemble Blouse		■				■	■	
FR Combat Ensemble Trousers		■				■	■	
Wind Pro Jacket					■	■	■	
Lightweight Exposure Suit Jacket	■	■	■	■		■	■	■
Lightweight Exposure Suit Trousers	■	■	■	■		■	■	■
Exteme Cold Weather Parka				■	■			
Extreme Cold Weather Trousers				■	■			
Snow Camouflage Parka							■	■
Snow Camouflage Trouser							■	■

THERMAL MANIKIN EVALUATIONS

Testing Methods

Biophysical clothing properties, thermal resistance (R_t) and evaporative resistance (R_{et}), were measured according to ASTM standards on a whole-body sweating thermal manikin [11, 12]. Thermal resistance measurements were performed with environmental conditions set to an air temperature (T_a) of 20ºC, 50% relative humidity (RH) and air velocity (v_a) of 0.4 m/s. Evaporative resistance measurements were performed with environmental conditions set to T_a of 35ºC, 40% RH and v_a of 0.4 m/s. Further background on biophysical clothing properties can be found in Appendix B. Two separate manikins were used throughout this study, both 20-zone Newton model manikins (Thermetrics, Seattle, WA, USA). The major difference between these two thermal manikins is that one manikin, part number 354, has power, communication and fluid cables connected through the face zone and the other manikin, part number 427, has cables connected through the navel. Garments and ensembles were tested on a thermal manikin with no additional equipment or accessories on the head, hand, or foot regions, with a few exceptions for tests with the USMC clothing system.

This study focused on the thermal resistances and evaporative resistances provided at torso, arm, and leg regions, areas typically covered by the clothing portion of a cold-weather clothing system. Head, hand and foot regional data values are included, however as they provide partial resistances; particularly in those situations where the clothing items and/or configurations extended onto the head, hand, or foot regions. In cases where the jacket included a hood, the garment or ensemble may have been tested with the hood down, the hood up, or both. For the data analysis and derivation of the equations, the hood down variation was used whenever possible due to the majority of ensemble variations being tested with the hood down. However, there were a few exceptions of the CAF system only having measurements with the hood up.

The configuration of the hood is of little relevance for the data analysis of this study. Of the three regions focused on in this study, only the torso region is directly affected by the hood (e.g., when a hood is not worn over the head and lays flat on the back of the user). There is an average percent difference of 3% between the torso region R_t of the hood up and hood down variations of the same configuration or garment, which is within the acceptable test-to-test variability for thermal resistance measurements [12].

Biophysical Properties of Boundary Air Layer

The thermal resistance of the boundary air layer (R_a) and the evaporative resistance of the boundary air layer (R_{ea}) were measured using a nude manikin prior to the start of measuring R_t and R_{et} of each clothing system. Because the tests utilized two separate manikins (ID # 354, ID # 427) and two environmental chambers (USARIEM Room 131 and USARIEM Room 232C) a potential source of variability was created. Accordingly, a code was created for each environmental chamber and manikin ID (EC_MI) combination using a format of: R<Environmental Chamber>_M<Manikin ID>. The environmental chamber is distinguished by the room number in USARIEM where the chamber resides, preceded by the letter R, and the Manikin ID is the manikin part number provided by the manikin manufacturer, preceded by the letter M. The three EC_MI combinations that were used for this study were R131_M354, R232C_M354, and R131_M427. The difference of the boundary air layer measurements in the EC_MI combinations at USARIEM have been examined previously. It was found that thermal and evaporative resistances of the boundary air layer have a percent difference of less than 10% [13].

Calculations of Biophysical Properties

In order to have the necessary clothing properties for USARIEM's cold weather thermoregulatory modeling software, previously created MATLAB® scripts [14] were used to create a database of thermal manikin properties for six body regions: head, torso, arm, hand, leg, and foot. The script takes the data from each of the 20 individual thermal manikin zones and calculates the weighted average of the six regional resistances using the parallel method:

$$R_{wtd(parallel)} = \frac{A_{tot}}{\sum A_i/R_i} \qquad \text{(Eq. 1)}$$

where A_i and R_i are the surface area and resistance, respectively, of each individual zone within each region, and A_{tot} is the total area of all zones within the region for which the parallel weighted average is being calculated. For example, when calculating the regional resistance for the head region (made up of two zones), the A_i values are the surface areas of the two zones in the head region. In a similar fashion, the R_i values are the two resistance values of the two zones in the head region. A_{tot} is the sum of the surface area for the two zones in the head region. Eq. 1 can be applied for either R_t or R_{et}. Further details on this process can be found in Rioux et al. 2016 [14].

Thermal and evaporative resistance values measured on a thermal manikin are typically values of total resistance. That is, total resistance of the clothing sample (garment or ensemble) and the resistance of the boundary air layer [15]. The intrinsic thermal resistance (R_{cl}) and intrinsic evaporative resistance (R_{ecl}) values are the resistances of the clothing, not including the boundary air layer. The intrinsic resistances are calculated by Eq. 2 for thermal resistance and Eq. 3 for evaporative resistance:

$$R_{cl} = R_t - \left(\frac{R_a}{f_{cl}}\right) \quad \text{(Eq. 2)}$$

$$R_{ecl} = R_{et} - \left(\frac{R_{ea}}{f_{cl}}\right) \quad \text{(Eq. 3)}$$

where R_{cl}, R_t, and R_a are in clo units (see Appendix B for more information on clo units); R_{ecl}, R_{et}, and R_{ea} are in m^2Pa/W; and f_{cl} is the dimensionless clothing area factor, which represents the increase of surface area due to clothing and can be calculated by:

$$f_{cl} = \frac{A_{cl}}{A_o} \quad \text{(Eq. 4)}$$

where A_{cl} is the surface area of a clothed manikin and A_o is the surface area of a nude manikin. Any unit of surface area can be used as long as the units of A_{cl} and A_o are consistent. It is also important to note the R_a and R_{ea} used to calculate the intrinsic resistances should match the EC_MI combinations where the clothing systems were tested.

This report presents resistances as intrinsic values. An f_{cl} of 1 was used for all intrinsic calculations, as f_{cl} is time consuming to measure directly and estimations can be inaccurate, while ultimately not having a large impact on the intrinsic value [16, 17]. Additionally, an f_{cl} of 1 will produce a conservative estimate in terms of thermoregulatory modeling results, meaning that resistances will be lower than using a measured or estimated f_{cl}, and exposure time estimates until threshold for cold injury will be more likely to recommend that Soldiers be removed from environments prior to injury. When an f_{cl} of 1 is used to calculate the intrinsic resistances (sometimes referred to as effective thermal and effective evaporative resistances), Eqs. 2 and 3 can be simplified to Eqs. 5 and 6, respectively:

$$R_{cl} = R_t - R_a \quad \text{(Eq. 5)}$$

$$R_{ecl} = R_{et} - R_{ea} \quad \text{(Eq. 6)}$$

Intrinsic resistances (f_{cl} = 1) of all garments and ensembles were calculated for each of the six body regions using the appropriate R_a and R_{ea} values. When the resistance calculations produced a negative value, it was replaced with the value of 0.00.

PREDICTION OF ENSEMBLE BIOPHYSICAL PROPERTIES

Methods to calculate the biophysical clothing properties of ensembles based on the measurements of individual garments have been developed previously [18]. However, the methods were derived from whole-body values and therefore prone to errors if the ensemble does not have relatively uniform resistances throughout all body regions. Deriving new equations for more localized regions is a more rational method and is necessary for use in USARIEM's decision aid software applications [7] and to improve accuracy of predictions. Linear regression analysis was performed to create equations that predict the regional intrinsic resistances of clothing ensembles based on the sum of the regional intrinsic resistances of individual garments. Plots of ensemble intrinsic resistance versus the sum of individual garment intrinsic resistance were created for thermal resistances and evaporative resistances for three body regions: torso, arm, and leg. Similar plots were created for whole-body measurements as a baseline for comparing accuracy. Trend lines of linear regressions were forced through the origin to be consistent with the case when no clothing is worn on a body region. In other words, if there are no garments worn on a region, the intrinsic sum of garment resistances should equal zero.

RESULTS

THERMAL MANIKIN EVALUATIONS

Boundary Air Layer

Thermal resistance measurements of the boundary air layer, i.e., the measured thermal resistance of the nude manikin, for the three EC_MI combinations are listed in Table 2. R131_M427 is listed twice because the USMC cold-weather clothing system and the SOF cold-weather clothing systems were tested four years apart. These values are provided for reference and to allow the reader to calculate the total thermal resistance (f_{cl} = 1).

Table 2. Thermal resistance of the boundary air layer

	Thermal Resistance of Boundary Air Layer, R_a (clo)						
	Whole Body	Head	Torso	Arm	Hand	Leg	Foot
R131_M354	0.69	0.79	0.85	0.69	0.57	0.64	0.55
R232C_M354	0.63	0.64	0.75	0.60	0.51	0.56	0.61
R131_M427 (SOF)	0.64	0.72	0.80	0.64	0.52	0.55	0.57
R131_M427 (USMC)	0.66	0.75	0.83	0.64	0.54	0.57	0.57

Evaporative resistance measurements of the boundary air layer, i.e., the measured evaporative resistance of the nude manikin for the three EC_MI combinations are listed in Table 3. Again, R131_M427 is listed twice due to the length of time between testing the USMC cold-weather clothing system and the SOF cold-weather clothing system. These values are provided for reference and to allow the reader to calculate the total evaporative resistance (f_{cl} = 1).

Table 3. Evaporative resistance of the boundary air layer

	Evaporative Resistance, R_{ea} (m^2Pa/W)						
	Whole Body	Head	Torso	Arm	Hand	Leg	Foot
R131_M354	13.8	18.8	19.2	13.2	10.4	12.6	10.0
R232C_M354	11.7	13.7	15.2	10.6	10.1	9.5	13.8
R131_M427 (SOF)	12.5	15.9	17.2	11.3	9.2	10.6	10.1
R131_M427 (USMC)	12.9	18.5	17.5	12.3	9.3	11.0	9.3

Garments

The R_{cl} values for each individual garment of the SOF cold-weather clothing system are presented in Table 4. The Stem Shell jacket and the Nano Air vest were not included in any ensemble configurations tested to date. The SOF clothing system testing was completed using R131_M427.

Table 4. Intrinsic thermal resistance of garments from the Special Operations Forces cold-weather clothing system

	Intrinsic Thermal Resistance, R_{cl} (clo)						
	Whole Body	Head	Torso	Arms	Hands	Legs	Feet
LW Long Sleeve Crew Shirt	0.15	0.00	0.59	0.43	0.07	0.03	0.00
LW Boxer Briefs	0.04	0.00	0.09	0.00	0.00	0.07	0.00
MW Quarter Zip	0.16	0.00	0.66	0.36	0.07	0.02	0.02
MW Long John	0.10	0.03	0.07	0.00	0.00	0.25	0.02
Nano Air Hoody Down	0.34	0.10	2.34	2.04	0.04	0.02	0.00
Nano Air Hoody Up	0.40	1.06	2.47	2.00	0.06	0.02	0.00
Nano Air Vest	0.17	0.00	2.00	0.06	0.04	0.01	0.00
Nano Air Bottom	0.34	0.00	0.29	0.00	0.00	1.75	0.03
Stem Shell Jacket Hood Down	0.18	0.04	0.69	0.50	0.03	0.02	0.01
Stem Shell Jacket Hood Up	0.20	0.50	0.68	0.52	0.03	0.02	0.01
Mixed Range Jacket Hood Down	0.20	0.04	0.75	0.67	0.03	0.03	0.00
Mixed Range Jacket Hood Up	0.22	0.34	0.74	0.64	0.03	0.04	0.00
Mixed Range Pants	0.21	0.01	0.16	0.00	0.00	0.71	0.05
Pneumo Fuse Top	0.22	0.00	1.05	0.90	0.03	0.01	0.02
Pneumo Fuse Bottom	0.24	0.00	0.20	0.00	0.00	0.75	0.09
DAS Jacket Hood Down	0.44	0.18	4.70	2.94	0.07	0.05	0.01
DAS Jacket Hood Up	0.50	1.40	4.63	2.99	0.07	0.05	0.00
DAS Pants	0.38	0.00	0.28	0.00	0.00	2.60	0.09
Helo Parka Hood Down	0.93	0.12	3.47	3.24	0.14	0.79	0.03
Helo Parka Hood Up	1.09	1.44	3.46	3.25	0.13	0.80	0.03

The R_{cl} values for each individual garment of the CAF cold-weather clothing system are listed in Table 5. The CAF clothing system testing was completed using R232C_M354.

Table 5. Intrinsic thermal resistance of garments from the Canadian Armed Forces cold-weather clothing system

	Intrinsic Thermal Resistance, R_{cl} (clo)						
	Whole Body	Head	Torso	Arms	Hands	Legs	Feet
Thermal Undershirt	0.21	0.00	0.85	0.58	0.05	0.04	0.00
Long Johns	0.15	0.00	0.12	0.00	0.00	0.48	0.01
CADPAT Fleece Jacket	0.39	0.01	2.80	1.80	0.20	0.05	0.00
CADPAT Fleece Trousers	0.29	0.00	0.29	0.00	0.00	1.21	0.04
CADPAT ICE Jacket	0.26	0.07	1.44	1.10	0.03	0.00	0.00
CADPAT ICE Trousers	0.29	0.00	0.24	0.00	0.00	1.39	0.08
CADPAT IECS Parka Hood Down	0.46	0.00	4.68	3.03	0.23	0.05	0.00
CADPAT IECS Parka Hood Up	0.55	0.74	4.75	2.95	0.21	0.06	0.00
CADPAT IECS Bib Pants	0.42	0.00	0.83	0.00	0.00	1.79	0.00
Canada Goose Snow Mantra Winter Parka	0.76	1.74	7.03	5.15	0.13	0.17	0.00

The R_{cl} values for each individual garment of the NAF cold-weather clothing system are listed in Table 6. The NAF clothing system testing was completed using R232C_M354.

Table 6. Intrinsic thermal resistance of garments from the Norwegian Armed Forces cold-weather clothing system

	Intrinsic Thermal Resistance, R_{cl} (clo)						
	Whole Body	Head	Torso	Arms	Hands	Legs	Feet
Net Undershirt	0.12	0.00	0.41	0.29	0.02	0.02	0.00
Net Underwear	0.10	0.00	0.11	0.00	0.00	0.26	0.01
Wool Terry Cloth Undershirt	0.14	0.02	0.79	0.77	0.03	0.00	0.02
Wool Terry Cloth Underwear	0.15	0.00	0.15	0.00	0.00	0.45	0.05
Cotton Field Shirt	0.25	0.04	0.98	0.71	0.07	0.05	0.00
M/02 Membrane Field Jacket Hood Down	0.27	0.00	1.38	0.72	0.11	0.04	0.00
M/02 Membrane Field Jacket Hood Up	0.31	0.38	1.30	0.74	0.09	0.05	0.00
M/02 Membrane Field Pants	0.21	0.00	0.21	0.00	0.00	0.69	0.01
M/97 Camouflage Jacket (white) Hood Down	0.34	0.00	1.01	0.74	0.34	0.16	0.00
M/97 Camouflage Jacket (white) Hood Up	0.38	0.31	0.94	0.76	0.37	0.17	0.00
M/97 Camouflage Trouser (white)	0.21	0.00	0.21	0.00	0.00	0.78	0.02
Cold Weather Jacket	0.40	0.02	3.41	3.24	0.14	0.02	0.00
Cold Weather Trousers	0.44	0.00	0.59	0.01	0.06	2.32	0.01

The R_{cl} values for each individual garment of the ECWCS cold-weather clothing system are listed in Table 7. The wind jacket was the only individual ECWCS garment not included in any ensemble configurations. The ECWCS clothing system testing was completed using R232C_M354.

Table 7. Intrinsic thermal resistance of garments from the U.S. Army's Generation III Extended Cold Weather Clothing System

	Intrinsic Thermal Resistance, R_{cl} (clo)						
	Whole Body	Head	Torso	Arms	Hands	Legs	Feet
Lightweight Undershirt	0.15	0.00	0.55	0.41	0.09	0.01	0.01
Lightweight Drawers	0.13	0.00	0.14	0.00	0.00	0.34	0.02
Midweight Shirt	0.19	0.03	0.69	0.68	0.16	0.00	0.00
Midweight Drawers	0.19	0.00	0.17	0.00	0.01	0.59	0.03
Fleece Jacket	0.26	0.05	1.05	1.32	0.06	0.01	0.02
Wind Jacket	0.18	0.00	0.70	0.55	0.03	0.01	0.02
Soft Shell Jacket	0.21	0.03	0.95	0.65	0.02	0.01	0.02
Soft Shell Trouser	0.24	0.00	0.29	0.00	0.02	0.75	0.00
Extreme Cold/Wet Weather Jacket	0.21	0.02	0.88	0.69	0.04	0.01	0.01
Extreme Cold/Wet Weather Trouser	0.22	0.00	0.20	0.00	0.05	0.70	0.02
Extreme Cold Weather Parka	0.39	0.00	3.69	2.94	0.14	0.01	0.00
Extreme Cold Weather Trouser	0.37	0.00	0.34	0.00	0.06	2.50	0.00

The R_{cl} values for each individual garment of the USMC cold-weather clothing system are listed in Table 8. The individual garments of the USMC clothing system were tested using R131_M354 (the USMC ensembles were tested on R131_M427).

Table 8. Intrinsic thermal resistance of garments from the U.S. Marine Corps cold-weather clothing system

	Intrinsic Thermal Resistance, R_{cl} (clo)						
	Whole Body	Head	Torso	Arms	Hands	Legs	Feet
Silkweight Undershirt	0.13	0.00	0.72	0.37	0.03	0.00	0.05
Silkweight Drawers	0.11	0.00	0.11	0.00	0.03	0.21	0.05
Grid Fleece Pullover	0.17	0.00	0.95	0.60	0.03	0.00	0.09
Grid Fleece Drawers	0.16	0.00	0.13	0.00	0.02	0.45	0.06
FR Combat Ensemble Blouse	0.15	0.00	0.71	0.75	0.02	0.00	0.05
FR Combat Ensemble Trousers	0.20	0.00	0.16	0.00	0.00	0.59	0.14
Wind Pro Jacket	0.25	0.05	1.18	1.17	0.07	0.01	0.00
Lightweight Exposure Suit Jacket	0.13	0.00	0.68	0.67	0.01	0.00	0.00
Lightweight Exposure Suit Trousers	0.18	0.00	0.16	0.00	0.00	0.58	0.06
Exteme Cold Weather Parka	0.32	0.00	3.52	2.62	0.03	0.00	0.06
Extreme Cold Weather Trousers	0.31	0.00	0.24	0.00	0.00	1.53	0.06
Snow Camouflage Parka	0.24	0.23	0.96	0.77	0.11	0.00	0.04
Snow Camouflage Trouser	0.17	0.00	0.12	0.00	0.04	0.53	0.03

The R_{ecl} values for each individual garment of the SOF cold-weather clothing system are listed in Table 9. The Stem Shell jacket and the Nano Air vest were not included in any ensemble configurations tested to date. As with thermal resistance garment measurements, the evaporative resistances of the SOF garments were measured using R131_M427.

Table 9. Intrinsic evaporative resistance of garments from Special Operations Forces cold-weather clothing system

	Intrinsic Evaporative Resistance, R_{ecl} (m^2Pa/W)						
	Whole Body	Head	Torso	Arms	Hands	Legs	Feet
LW Long Sleeve Crew Shirt	2.99	0.74	12.32	12.39	1.31	0.00	0.00
LW Boxer Briefs	0.96	0.70	1.14	0.57	0.00	1.88	0.00
MW Quarter Zip	3.22	0.00	12.88	10.51	1.79	0.32	0.00
MW Long John	1.77	0.52	0.55	0.45	0.00	5.26	0.00
Nano Air Hoody Down	6.39	1.31	35.59	38.49	1.99	0.37	1.53
Nano Air Hoody Up	6.95	18.06	36.59	37.40	1.35	0.20	1.35
Nano Air Vest	2.67	0.85	27.60	2.44	0.10	0.00	0.14
Nano Air Bottom	6.20	0.11	3.88	0.31	0.00	35.93	0.31
Stem Shell Hood Down	4.64	0.00	27.92	28.25	0.35	0.05	0.00
Stem Shell Hood Up	5.60	16.89	30.65	27.61	0.88	0.00	0.00
Mixed Range Jacket Hood Down	3.91	1.07	14.63	19.16	0.68	0.12	0.43
Mixed Range Jacket Hood Up	4.78	11.17	19.15	18.92	1.38	0.00	0.93
Mixed Range Pants	5.50	0.36	2.22	0.40	0.00	27.74	1.76
Pneumo Fuse Top	4.09	0.79	17.60	23.96	0.59	0.00	0.34
Pneumo Fuse Bottom	4.67	0.40	2.57	0.00	0.00	19.10	1.08
DAS Jacket Hood Down	7.64	4.26	82.43	63.90	1.81	0.00	1.12
DAS Jacket Hood Up	8.30	22.04	77.36	62.51	2.46	0.00	0.86
DAS Pants	7.53	1.18	5.36	0.15	0.00	53.72	1.04
Helo Parka Hood Down	20.36	3.26	114.00	71.30	7.30	14.71	1.23
Helo Parka Hood Up	21.65	25.10	106.38	84.53	1.53	14.79	1.13

The R_{ecl} values for each individual garment of the CAF cold-weather clothing system are listed in Table 10. As with the thermal resistance garment measurements, the evaporative resistances of the CAF garments were measured using R232C_M354.

Table 10. Intrinsic evaporative resistance of garments from the Candian Armed Forces cold-weather clothing system

	Intrinsic Evaporative Resistance, R_{ecl} (m^2Pa/W)						
	Whole Body	Head	Torso	Arms	Hands	Legs	Feet
Thermal Undershirt	3.58	0.00	14.92	12.70	4.66	0.24	0.00
Long Johns	3.36	0.00	1.90	1.03	1.97	8.00	0.00
CADPAT Fleece Jacket	7.19	0.87	82.71	61.54	6.52	0.16	0.00
CADPAT Fleece Trousers	6.41	0.00	5.49	0.00	2.69	28.97	0.00
CADPAT ICE Jacket	6.85	1.15	68.74	54.32	1.35	0.25	0.00
CADPAT ICE Trousers	8.17	0.00	6.49	0.00	2.29	54.14	1.02
CADPAT IECS Parka Hood Down	6.34	0.19	78.51	80.69	2.64	0.00	0.00
CADPAT IECS Parka Hood Up	9.22	36.25	137.71	87.03	4.08	0.01	0.00
CADPAT IECS Bib Pants	10.07	0.00	14.08	0.00	3.27	68.42	0.00
Canada Goose Snow Mantra Winter Parka	13.01	72.71	153.49	167.82	5.79	1.75	0.00

The R_{ecl} values for each individual garment of the NAF cold-weather clothing system are listed in Table 11. As with the thermal resistance garment measurements, the evaporative resistances of the NAF garments were measured using R232C_M354.

Table 11. Intrinsic evaporative resistance of garments from the Norwegian Armed Forces cold-weather clothing system

	Intrinsic Evaporative Resistance, R_{ecl} (m^2Pa/W)						
	Whole Body	Head	Torso	Arms	Hands	Legs	Feet
Net Undershirt	1.55	0.00	7.25	4.74	0.00	0.00	0.00
Net Underwear	1.69	0.00	0.48	0.00	1.30	4.54	0.00
Wool Terry Cloth Undershirt	1.80	1.84	17.74	15.06	0.00	0.00	0.00
Wool Terry Cloth Underwear	2.70	0.00	1.44	0.00	0.00	7.73	0.00
Cotton Field Shirt	5.46	1.61	21.73	27.41	6.84	0.80	0.00
M/02 Membrane Field Jacket Hood Down	6.07	0.91	46.79	34.91	2.28	0.32	0.00
M/02 Membrane Field Jacket Hood Up	7.72	18.08	41.68	34.13	2.10	1.21	0.00
M/02 Membrane Field Pants	6.48	0.00	6.07	0.00	0.00	36.21	0.00
M/97 Camouflage Jacket (white) Hood Down	7.69	0.00	31.49	24.20	0.48	3.64	0.00
M/97 Camouflage Jacket (white) Hood Up	7.79	11.31	33.71	21.41	0.55	2.57	0.00
M/97 Camouflage Trouser (white)	7.05	0.00	5.72	0.00	0.00	49.99	0.00
Cold Weather Jacket	9.53	1.35	74.65	141.80	1.27	1.75	0.43
Cold Weather Trousers	11.75	0.00	16.48	0.73	1.29	128.21	0.00

The R_{ecl} values for each individual garment of the ECWCS cold-weather clothing system are listed in Table 12. The wind jacket was the only individual ECWCS garment not included in any ensemble configurations. As with the thermal resistance garment measurements, the evaporative resistances of the ECWCS garments were measured using R232C_M354.

Table 12. Intrinsic evaporative resistance of garments from the U.S. Army's Generation III Cold Weather Clothing System

	Intrinsic Evaporative Resistance, R_{ecl} (m^2Pa/W)						
	Whole Body	Head	Torso	Arms	Hands	Legs	Feet
Lightweight Undershirt	2.89	0.00	9.86	6.52	0.00	1.02	0.00
Lightweight Drawers	3.21	0.00	3.31	1.03	0.00	6.81	1.04
Midweight Shirt	2.91	0.32	12.96	13.33	0.46	0.00	0.00
Midweight Drawers	3.40	0.00	3.41	0.01	0.00	10.08	0.00
Fleece Jacket	3.65	0.47	14.20	21.70	0.00	0.03	0.00
Wind Jacket	2.87	0.00	13.63	16.27	0.00	0.00	0.00
Soft Shell Jacket	5.08	0.09	46.13	55.94	0.00	0.00	0.00
Soft Shell Trouser	9.40	0.00	8.06	0.95	2.20	70.57	0.00
Extreme Cold/Wet Weather Jacket	4.68	0.00	34.25	31.81	0.00	0.00	0.11
Extreme Cold/Wet Weather Trouser	6.28	0.00	5.58	0.00	0.00	39.38	0.00
Extreme Cold Weather Parka	5.72	0.00	65.91	65.41	0.46	0.00	0.00
Extreme Cold Weather Trouser	8.17	0.00	7.41	0.60	0.00	69.06	0.00

The R_{ecl} values for each individual garment of the USMC cold-weather clothing system are listed in Table 13. As with the thermal resistance garment measurements, the evaporative resistances of the USMC garments were measured using R131_M354 (the USMC ensembles were tested on R131_M427).

Table 13. Intrinsic evaporative resistance of garments from the U.S.Marine Corps cold-weather clothing system

	Intrinsic Evaporative Resistance, Recl (m^2Pa/W)						
	Whole Body	Head	Torso	Arms	Hands	Legs	Feet
Silkweight Undershirt	2.48	0.00	15.23	6.89	2.09	0.00	1.17
Silkweight Drawers	1.70	0.00	0.72	0.00	1.50	2.91	0.47
Grid Fleece Pullover	3.23	0.00	15.84	14.39	4.83	0.00	0.33
Grid Fleece Drawers	3.36	0.00	1.59	0.00	1.44	9.26	0.30
FR Combat Ensemble Blouse	3.80	0.00	18.07	25.69	1.31	0.00	1.48
FR Combat Ensemble Trousers	5.71	0.00	0.98	0.00	4.29	24.34	3.07
Wind Pro Jacket	4.30	0.00	24.76	24.17	1.70	0.00	0.00
Lightweight Exposure Suit Jacket	4.15	0.00	15.05	32.54	2.40	0.00	0.61
Lightweight Exposure Suit Trousers	7.11	0.00	4.46	0.00	1.58	33.39	1.12
Exteme Cold Weather Parka	5.95	0.00	54.94	90.91	3.68	0.00	0.42
Extreme Cold Weather Trousers	7.63	0.00	2.17	0.00	4.29	48.17	4.08
Snow Camouflage Parka	5.48	7.95	23.80	22.01	3.84	0.00	1.59
Snow Camouflage Trouser	6.36	0.00	3.17	0.30	7.49	19.57	1.47

Ensembles

The R_{cl} values for the ensemble configurations of the SOF cold-weather clothing system are listed in Table 14. The SOF clothing system testing was completed using the R131_M427.

Table 14. Intrinsic thermal resistance of the Special Operations Forces cold-weather ensembles

	Intrinsic Thermal Resistance, R_{cl} (clo)						
	Whole Body	Head	Torso	Arms	Hands	Legs	Feet
Ensemble 1 Hood Down	1.55	0.18	5.34	3.50	0.10	2.99	0.06
Ensemble 1 Hood Up	1.84	1.46	5.10	3.45	0.10	3.02	0.07
Ensemble 2 Hood Down	1.56	0.14	4.80	3.40	0.11	3.07	0.12
Ensemble 2 Hood Up	1.91	1.63	4.67	3.40	0.13	3.08	0.15
Ensemble 3 Hood Down	1.88	0.20	7.96	5.23	0.18	3.61	0.12
Ensemble 3 Hood Up	2.27	2.04	7.29	5.08	0.15	3.62	0.13
Ensemble 4 Hood Down	1.61	0.25	6.11	3.89	0.11	2.93	0.05
Ensemble 4 Hood Up	1.94	1.78	6.05	3.96	0.11	3.02	0.07
Ensemble 5 Hood Down	1.25	0.10	3.72	2.42	0.07	2.19	0.06
Ensemble 5 Hood Up	1.49	1.44	3.71	2.40	0.07	2.21	0.06
Ensemble 6 Hood Down	1.63	0.24	5.58	3.58	0.11	3.19	0.07
Ensemble 6 Hood Up	1.92	1.37	5.44	3.60	0.15	3.21	0.08

The R_{cl} values for the ensemble configurations of the CAF cold-weather clothing system are listed in Table 15. The CAF clothing system testing was completed using the R232C_M354.

Table 15. Intrinsic thermal resistance of the Canadian Armed Forces cold-weather ensembles

	Intrinsic Thermal Resistance, R_{cl} (clo)						
	Whole Body	Head	Torso	Arms	Hands	Legs	Feet
Ensemble 1 Hood Down	1.19	0.03	3.07	1.99	0.18	1.99	0.13
Ensemble 2 Hood Down	1.48	0.01	5.91	3.41	0.28	2.89	0.01
Ensemble 2 Hood Up	1.82	0.81	5.83	3.29	0.27	2.84	0.02
Ensemble 3 Hood Down	1.70	0.07	7.37	4.38	0.19	3.99	0.03
Ensemble 3 Hood Up	2.03	0.87	6.96	4.28	0.18	4.00	0.01
Ensemble 4 Hood Up	2.48	1.89	8.91	5.74	0.27	4.48	0.02
Ensemble 5 Hood Up	2.01	0.94	6.18	3.90	0.22	3.09	0.12
Ensemble 6 Hood Up	1.88	1.96	9.23	5.95	0.20	1.73	0.04

The R_{cl} values for the ensemble configurations of the NAF cold-weather clothing system are listed in Table 16. The NAF clothing system testing was completed using the R232C_M354.

Table 16. Intrinsic thermal resistance of the Norwegian Armed Forces cold-weather ensembles

	Intrinsic Thermal Resistance, R_{cl} (clo)						
	Whole Body	Head	Torso	Arms	Hands	Legs	Feet
Ensemble 1 Hood Down	1.19	0.12	3.71	2.14	0.15	1.80	0.02
Ensemble 2 Hood Down	1.01	0.05	3.30	1.84	0.14	1.32	0.04
Ensemble 3 Hood Down	1.04	0.04	2.76	1.95	0.16	1.58	0.04
Ensemble 4 Hood Down	1.57	0.08	6.47	4.50	0.23	2.83	0.01
Ensemble 5 Hood Down	1.78	0.08	7.68	4.42	0.30	3.56	0.10

The R_{cl} values for the ensemble configurations of the ECWCS cold-weather clothing system are listed in Table 17. The ECWCS clothing system testing was completed using R232C_M354.

Table 17. Intrinsic thermal resistance of the U.S. Army's Generation III Extended Cold Weather Clothing System ensembles

	Intrinsic Thermal Resistance, R_{cl} (clo)						
	Whole Body	Head	Torso	Arms	Hands	Legs	Feet
Ensemble 1	0.65	0.00	1.33	0.93	0.18	0.86	0.03
Ensemble 2	0.89	0.05	2.69	2.17	0.21	0.88	0.03
Ensemble 3	1.10	0.05	3.62	2.34	0.13	1.56	0.01
Ensemble 4 Hood Up	2.18	0.93	6.83	4.96	0.30	4.17	0.02
Ensemble 4 Hood Down	1.68	0.08	7.52	4.41	0.13	4.06	0.03
Ensemble 5 Hood Down	0.86	0.02	2.19	1.23	0.09	1.41	0.01
Ensemble 6 Hood Down	1.20	0.04	5.71	3.70	0.11	1.48	0.02
Ensemble 7 Hood Down	0.72	0.03	1.54	1.00	0.05	1.18	0.00
Ensemble 8 Hood Down	0.69	0.00	1.38	0.98	0.09	1.09	0.02
Ensemble 9 Hood Down	0.93	0.05	2.93	2.16	0.06	1.10	0.04

The R_{cl} values for the ensemble configurations of the USMC cold-weather clothing system are listed in Table 18. The ensemble configurations of the USMC clothing system were tested using R131_M427 (the individual garments of the USMC clothing system were tested on R131_M354).

Table 18. Intrinsic thermal resistance of the U.S. Marine Corps cold-weather ensembles

	Intrinsic Thermal Resistance, R_{cl} (clo)						
	Whole Body	Head	Torso	Arms	Hands	Legs	Feet
Ensemble 1 Hood Down	0.86	0.37	1.35	1.05	0.05	1.16	0.33
Ensemble 2 Hood Down	1.09	0.40	1.82	1.59	0.01	1.65	0.35
Ensemble 3 Hood Down	1.14	0.41	1.97	1.54	0.21	1.48	0.33
Ensemble 4 Hood Down	1.87	0.38	4.95	3.47	0.22	2.93	0.37
Ensemble 5 Hood Down	1.87	0.41	5.44	4.24	0.20	2.53	0.38
Ensemble 6 Hood Down	1.31	0.43	3.16	2.27	0.06	1.60	0.35
Ensemble 7 Hood Down	1.60	0.44	3.84	2.84	0.14	2.23	0.37
Ensemble 8 Hood Down	1.24	0.39	2.12	1.73	0.13	1.80	0.40

The R_{ecl} values for the ensemble configurations of the SOF cold-weather clothing system are listed in Table 19. As with thermal resistance ensemble measurements, the evaporative resistances of the SOF ensembles were measured using R131_M427.

Table 19. Intrinsic evaporative resistance of the Special Operations Forces cold-weather ensembles

	Intrinsic Evaporative Resistance, R_{ecl} (m^2Pa/W)						
	Whole Body	Head	Torso	Arms	Hands	Legs	Feet
Ensemble 1 Hood Down	31.48	6.25	114.45	66.70	1.59	57.77	2.39
Ensemble 1 Hood Up	34.70	25.76	103.82	65.20	2.13	56.80	2.35
Ensemble 2 Hood Down	34.14	4.26	120.13	73.36	2.75	68.66	3.14
Ensemble 2 Hood Up	38.19	23.22	111.47	70.82	3.08	66.40	3.17
Ensemble 3 Hood Down	37.71	6.60	213.32	102.69	2.03	73.60	2.37
Ensemble 3 Hood Up	46.95	51.41	194.55	102.47	3.75	71.88	3.25
Ensemble 4 Hood Down	33.12	4.33	123.07	81.43	3.57	60.70	1.85
Ensemble 4 Hood Up	38.53	35.84	120.39	77.22	3.63	59.67	2.07
Ensemble 5 Hood Down	27.10	1.94	79.17	53.25	3.13	47.66	2.18
Ensemble 5 Hood Up	32.74	34.17	75.17	55.07	3.02	48.70	2.89
Ensemble 6 Hood Down	33.75	6.76	110.49	76.05	2.48	65.67	2.53
Ensemble 6 Hood Up	37.03	28.07	106.48	68.64	2.56	65.06	2.48

The R_{ecl} values for the ensemble configurations of the CAF cold-weather clothing system are listed in Table 20. As with the thermal resistance ensemble measurements, the evaporative resistances of the CAF ensembles were measured using R232C_M354.

Table 20. Intrinsic evaporative resistance of the Canadian Armed Forces cold-weather ensembles

	Intrinsic Evaporative Resistance, R_{ecl} (m^2Pa/W)						
	Whole Body	Head	Torso	Arms	Hands	Legs	Feet
Ensemble 1 Hood Down	31.05	0.00	78.22	71.83	5.47	67.98	1.51
Ensemble 2 Hood Down	32.34	0.00	126.82	91.72	4.99	85.41	0.00
Ensemble 2 Hood Up	43.69	27.94	125.25	86.63	5.05	88.24	0.00
Ensemble 3 Hood Down	36.12	1.22	170.05	92.86	4.02	95.39	0.00
Ensemble 3 Hood Up	45.88	39.17	166.24	93.79	2.67	93.96	0.00
Ensemble 4 Hood Up	51.88	67.27	189.16	149.30	1.91	101.20	0.00
Ensemble 5 Hood Down	38.59	2.57	153.08	76.94	1.78	92.05	3.39
Ensemble 6 Hood Up	42.19	68.63	180.11	159.53	5.03	38.01	0.00

The R_{ecl} values for the ensemble configurations of the NAF cold-weather clothing system are listed in Table 21. As with the thermal resistance ensemble measurements, the evaporative resistances of the NAF ensembles were measured using R232C_M354.

Table 21. Intrinsic evaporative resistance of the Norwegian Armed Forces cold-weather ensembles

	Intrinsic Evaporative Resistance, R_{ecl} (m^2Pa/W)						
	Whole Body	Head	Torso	Arms	Hands	Legs	Feet
Ensemble 1 Hood Down	35.54	1.22	103.03	70.29	7.53	82.28	0.00
Ensemble 2 Hood Down	31.38	3.90	98.91	71.17	3.79	49.07	0.00
Ensemble 3 Hood Down	26.86	1.51	59.27	47.67	3.44	63.76	0.00
Ensemble 4 Hood Down	45.85	2.13	195.80	163.64	8.57	148.48	0.00
Ensemble 5 Hood Down	52.24	2.29	314.45	179.14	7.24	179.60	1.74

The R_{ecl} values for the ensemble configurations of the ECWCS cold-weather clothing system are listed in Table 22. As with the thermal resistance ensemble measurements, the evaporative resistances of the ECWCS ensembles were measured using R232C_M354.

Table 22. Intrinsic evaporative resistance of the U.S. Army's Generation III Extended Cold Weather Clothing System ensembles

	Intrinsic Evaporative Resistance, R_{ecl} (m^2Pa/W)						
	Whole Body	Head	Torso	Arms	Hands	Legs	Feet
Ensemble 1	11.37	0.21	24.91	21.68	2.30	11.61	0.00
Ensemble 2	14.86	0.62	48.31	35.76	1.62	12.99	0.00
Ensemble 3	33.31	1.52	133.33	86.15	2.71	82.32	0.00
Ensemble 4 Hood Up	56.10	36.73	198.96	118.98	5.77	115.46	0.27
Ensemble 4 Hood Down	41.98	3.10	238.95	124.03	1.34	139.70	0.00
Ensemble 5 Hood Down	31.52	0.87	98.35	68.75	2.03	84.50	0.00
Ensemble 6 Hood Down	35.04	0.84	169.95	122.45	1.04	84.45	0.00
Ensemble 7 Hood Down	28.69	2.28	79.96	60.80	0.00	80.83	0.00
Ensemble 8 Hood Down	21.97	1.20	42.24	32.21	0.80	47.89	0.00
Ensemble 9 Hood Down	26.62	1.60	80.98	58.48	0.50	47.66	0.00

The R_{ecl} values for the ensemble configurations of the USMC cold-weather clothing system are listed in Table 23. As with the thermal resistance ensemble measurements, the evaporative resistances of the ensemble configurations of the USMC clothing system were tested using R131_M427 (the individual garments of the USMC clothing system were tested on R131_M354).

Table 23. Intrinsic evaporative resistance of the U.S. Marine Corps cold-weather ensembles

	Intrinsic Evaporative Resistance, R_{ecl} (m^2Pa/W)						
	Whole Body	Head	Torso	Arms	Hands	Legs	Feet
Ensemble 1 Hood Down	25.67	7.00	44.75	40.54	2.04	49.27	4.56
Ensemble 2 Hood Down	29.47	8.26	62.30	55.41	1.46	60.44	3.94
Ensemble 3 Hood Down	30.21	7.76	58.80	44.47	5.11	53.95	4.99
Ensemble 4 Hood Down	44.03	7.28	181.17	114.98	5.46	76.91	5.40
Ensemble 5 Hood Down	39.14	7.73	144.89	100.10	4.65	55.38	6.12
Ensemble 6 Hood Down	32.01	14.03	85.89	56.10	1.80	50.77	5.17
Ensemble 7 Hood Down	38.44	13.44	105.53	70.07	4.30	67.88	5.24
Ensemble 8 Hood Down	34.31	5.52	64.94	58.47	4.07	70.82	7.46

ENSEMBLE THERMAL RESISTANCE PREDICTIONS

The Plots of measured ensemble R_{cl} versus the sum of garment R_{cl} are shown in Figures 6-9 for torso, arm, leg, and whole-body regions, respectively. The resulting equations to predict ensemble R_{cl} for torso, arm, leg, and whole-body regions are presented in Eqs. 7-10, respectively:

$$y = 0.836x \qquad \text{(Eq. 7)}$$

$$y = 0.809x \qquad \text{(Eq. 8)}$$

$$y = 0.961x \qquad \text{(Eq. 9)}$$

$$y = 0.990x \qquad \text{(Eq. 10)}$$

where *y* is the predicted R_{cl} of the ensemble and *x* is the sum of the individual garment R_{cl} that constitute the ensemble. The R^2 values for torso, arm, leg, and whole-body regions are 0.924, 0.939, 0.854, and 0.655, respectively.

Figure 6. Torso Region – measured ensemble intrinsic thermal resistance versus sum of garment intrinsic thermal resistance

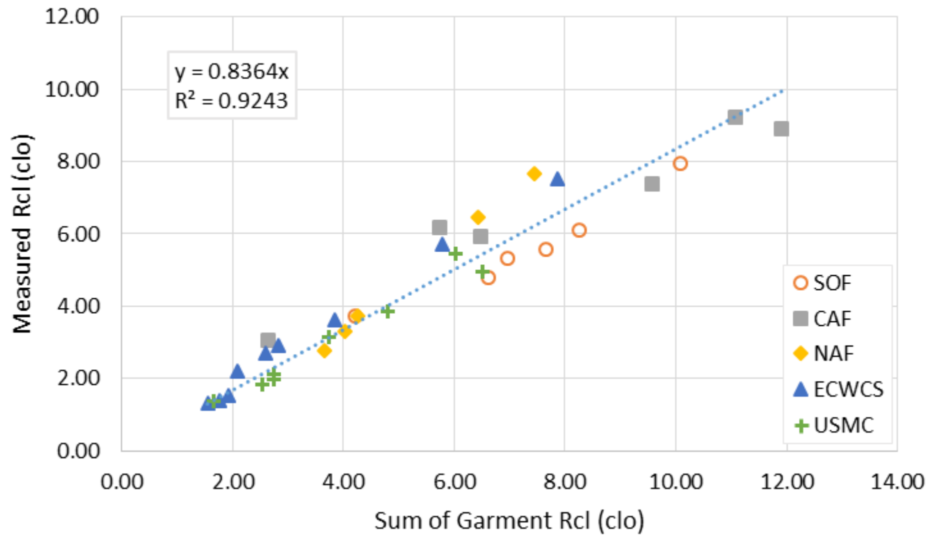


Figure 7. Arm Region – measured ensemble intrinsic thermal resistance versus sum of garment intrinsic thermal resistance

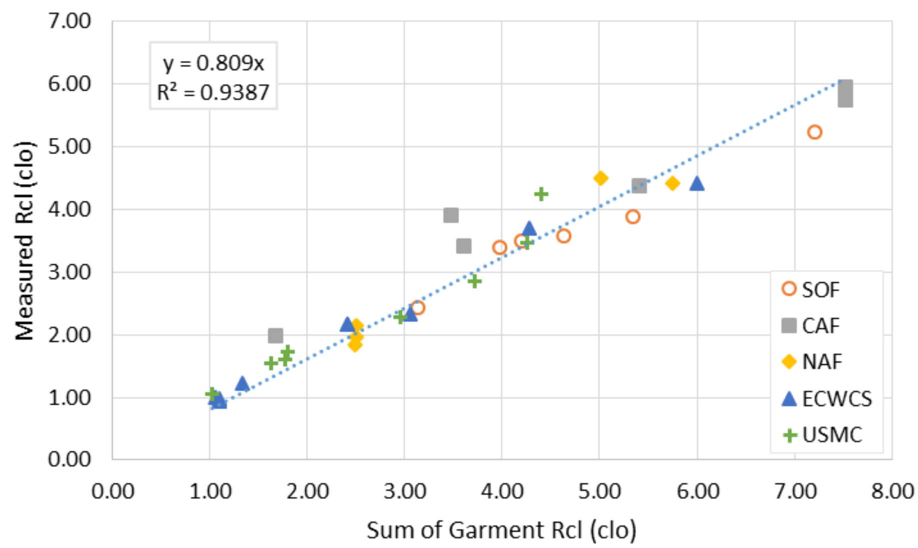


Figure 8. Leg Region – measured ensemble intrinsic thermal resistance versus sum of garment intrinsic thermal resistance

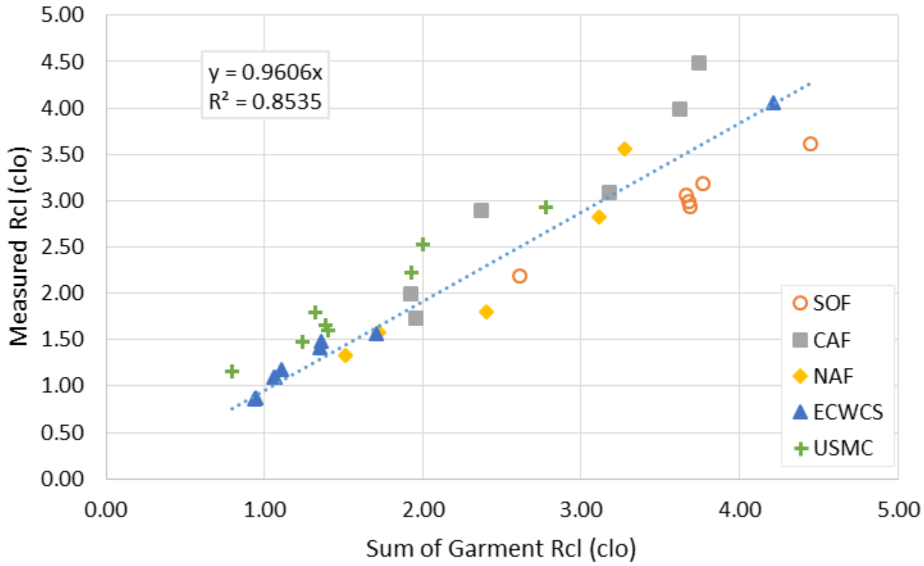
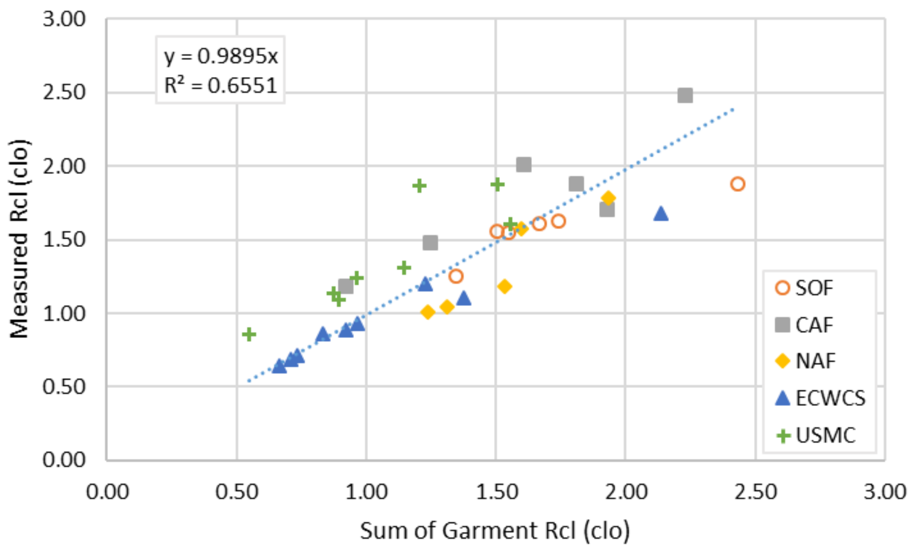


Figure 9. Whole body – measured ensemble intrinsic thermal resistance versus sum of garment intrinsic thermal resistance



ENSEMBLE EVAPORATIVE RESISTANCE PREDICTIONS

Plots of the measured ensemble R_{ecl} versus the sum of garment R_{ecl} are shown in Figures 10-13 for torso, arm, leg, and whole-body regions, respectively. The resulting equations to predict ensemble R_{ecl} for torso, arm, leg, and whole-body regions are presented in Eqs. 11-14, respectively:

$$y = 0.999x \quad \text{(Eq. 11)}$$

$$y = 0.737x \quad \text{(Eq. 12)}$$

$$y = 0.950x \quad \text{(Eq. 13)}$$

$$y = 1.12x \quad \text{(Eq. 14)}$$

where *y* is the predicted R_{ecl} of the ensemble and *x* is the sum of individual garment R_{ecl} that constitute the ensemble. The R^2 values for torso, arm, leg, and whole-body regions are 0.572, 0.851, 0.864, and 0.510, respectively.

Figure 10. Torso Region - measured ensemble intrinsic evaporative resistance versus sum of garment intrinsic evaporative resistance

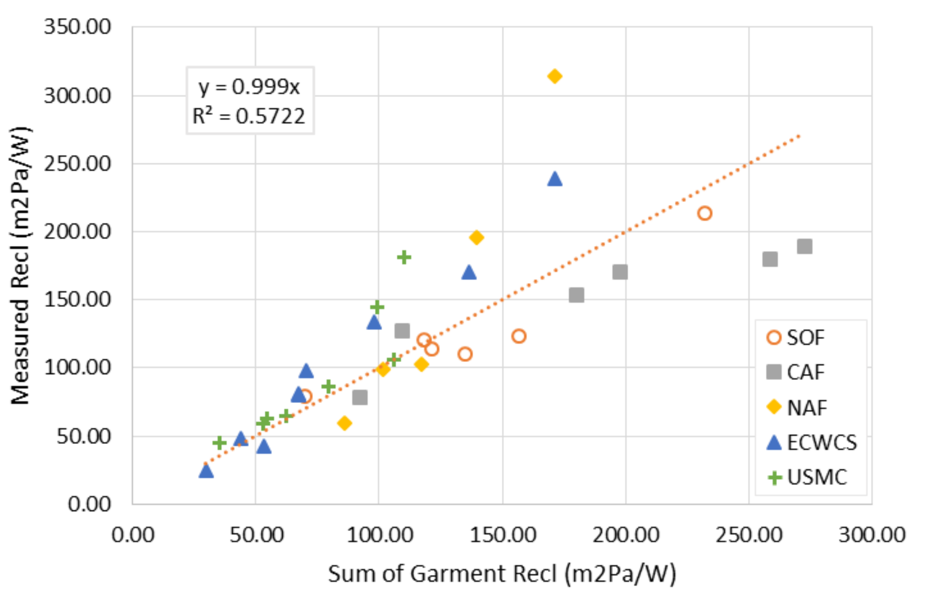


Figure 11. Arm Region - measured ensemble intrinsic evaporative resistance versus sum of garment intrinsic evaporative resistance

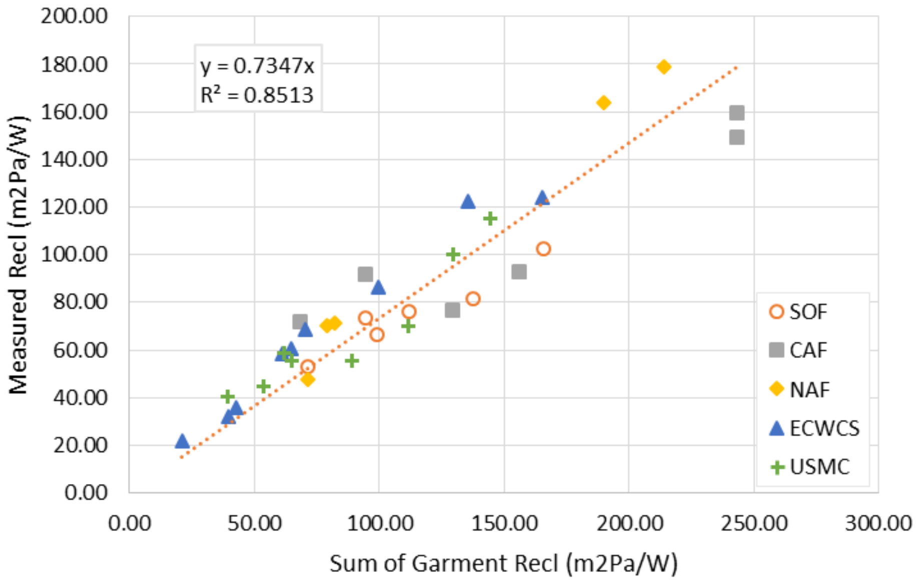


Figure 12. Leg Region - measured ensemble intrinsic evaporative resistance versus sum of garment intrinsic evaporative resistance

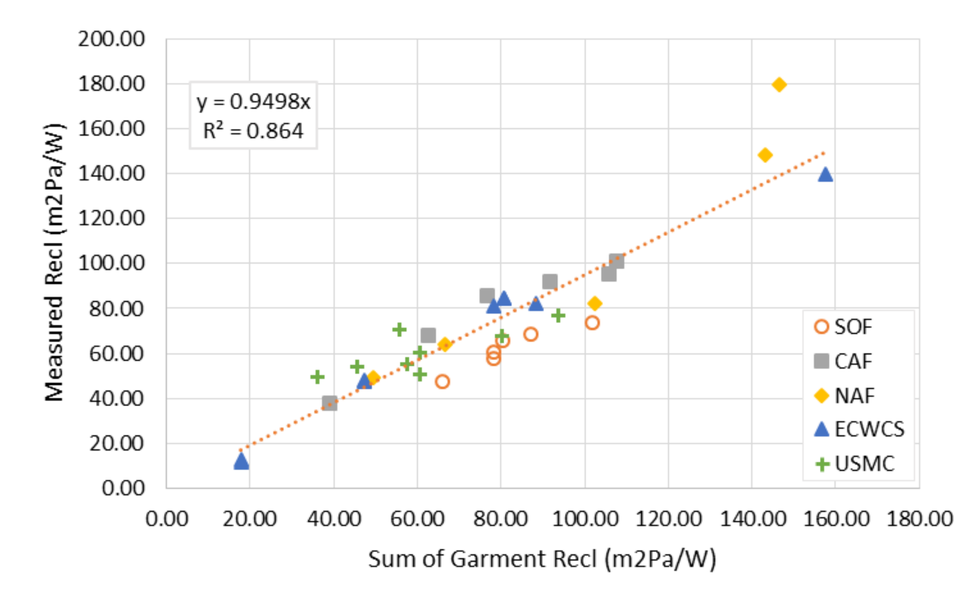
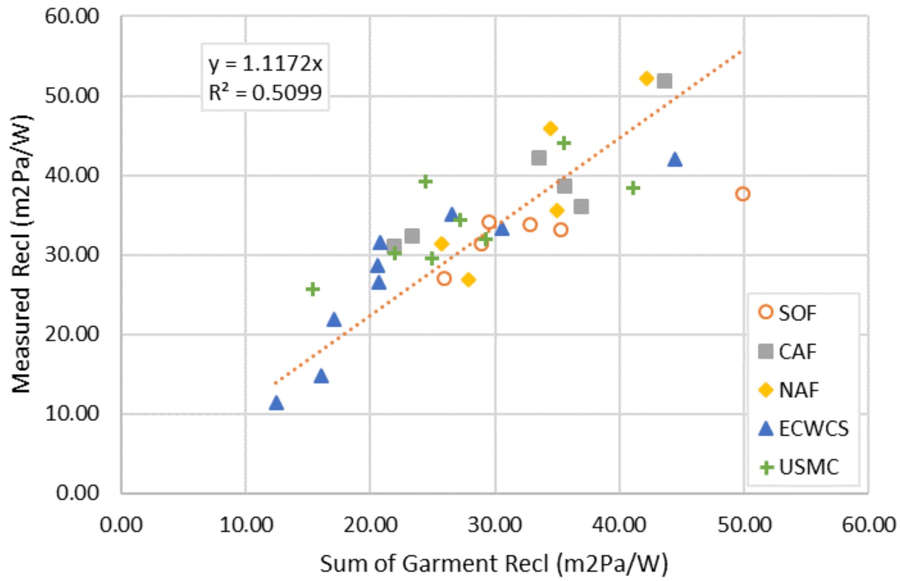


Figure 13. Whole body - measured ensemble intrinsic evaporative resistance versus sum of garment intrinsic evaporative resistance



DISCUSSION

This report shares the outcomes of a systematic evaluation of the thermal performance of five cold-weather clothing systems, the individual garments that compose them, and various ensemble configurations of these systems. The present study reports both whole-body and regional resistance values, and is the first study to develop equations that predict regional ensemble resistances from regional garment resistances. The derivation of acceptably accurate regional prediction equations is needed, as models that rely on whole-body resistance values can produce flawed or misleading results when the properties of the ensemble are not evenly distributed over all body regions. The R_{cl} measurements of the ECWCS Ensemble 4 (hood down) are an illustrative example of how a whole-body value does not provide adequate accuracy for thermoregulatory modeling. The single, whole-body R_{cl} of the ensemble is 1.7 clo. The R_{cl} values of the torso, arm, and leg regions are 7.5 clo, 4.4 clo and 4.1 clo, respectively, while the head, hand, and foot regional R_{cl} values are essentially 0.0 clo, as there are no clothing items on those regions. This means that the whole-body value alone does not provide enough information, especially for winter clothing that typically does not have uniform regional properties. This effect also shows that thermoregulatory models with single, whole-body clothing property input may not account for the unique physiological responses of body regions due to the varying resistances in those regions.

The five cold-weather clothing systems evaluated in this report each have multiple layers that serve various purposes, such as base layers, insulating layers, shell layers, and heavy insulation outer layers. All the layers in a given clothing system span a relatively large range of R_{cl} and R_{ecl} values and serve various functions. Attempts to compare the same general type of layer (e.g., base layers) still present challenges. For example, the CAF system only has one base layer option, while the other four systems have two different weights of base layers that are either worn together or individually. Additionally, the most ideal clothing may depend on the environmental exposure scenario. Despite these challenges, some general observations and comparisons can be made. One of the most likely scenarios that can be used for a basis of comparison for cold-weather clothing systems is extreme cold-weather exposure with a sedentary subject. In this case, a high R_{cl} and low R_{ecl} are ideal. The garments and ensembles with the highest three R_{cl} are listed in Tables 24-27 for the whole body, torso, arm, and leg regions, respectively. The garments and ensembles with the lowest three R_{ecl} are listed in Tables 28-31 for the whole body, torso, arm, and leg regions, respectively. ECWCS Ensembles 1 and 2 have the lowest R_{ecl} in most cases. However, these ensembles are not likely to be worn in any practical scenario and therefore are excluded from Tables 28-31.

Table 24. Highest three intrinsic thermal resistances of garments and ensembles based on the whole-body values

Whole Body		
Garments *Hood Down Only		R_{cl} (clo)
SOF	Helo Parka Hood Down	0.93
CAF	CADPAT IECS Parka Hood Down	0.46
SOF	DAS Jacket Hood Down	0.44
Ensembles *Hood Down Only		R_{cl} (clo)
CAF	Ensemble 5 Hood Down	2.01
SOF	Ensemble 3 Hood Down	1.88
USMC	Ensemble 4 Hood Down	1.87

Table 25. Highest three intrinsic thermal resistances of garments and ensembles based on torso region values

Torso Region		
Garments *Hood Down Only		R_{cl} (clo)
SOF	DAS Jacket Hood Down	4.70
CAF	CADPAT IECS Parka Hood Down	4.68
ECWCS	Extreme Cold Weather Parka	3.69
Ensembles *Hood Down Only		R_{cl} (clo)
SOF	Ensemble 3 Hood Down	7.96
NAF	Ensemble 5 Hood Down	7.68
ECWCS	Ensemble 4 Hood Down	7.52

Table 26. Highest three intrinsic thermal resistances of garments and ensembles based on arm region values

Arm Region		
Garments *Hood Down Only		R_{cl} (clo)
SOF	Helo Parka Hood Down	3.24
NAF	Cold Weather Jacket	3.24
CAF	CADPAT IECS Parka Hood Down	3.03
Ensembles *Hood Down Only		R_{cl} (clo)
SOF	Ensemble 3 Hood Down	5.23
NAF	Ensemble 4 Hood Down	4.50
NAF	Ensemble 5 Hood Down	4.42

Table 27. Highest three intrinsic thermal resistances of garments and ensembles based on leg region values

Leg Region		
Garments		R_{cl} (clo)
SOF	DAS Pants	2.60
ECWCS	Extreme Cold Weather Trouser	2.50
NAF	Cold Weather Trousers	2.32
Ensembles *Hood Down Only		R_{cl} (clo)
ECWCS	Ensemble 4 Hood Down	4.06
CAF	Ensemble 3 Hood Down	3.99
SOF	Ensemble 3 Hood Down	3.61

Table 28. Lowest three intrinsic evaporative resistances of garments and ensembles based on the whole-body values

Whole Body		
Garments		R_{ecl} (m^2Pa/W)
SOF	LW Boxer Briefs	0.96
NAF	Net Undershirt	1.55
NAF	Net Underwear	1.69
Ensembles *Hood Down Only		R_{ecl} (m^2Pa/W)
ECWCS	Ensemble 8 Hood Down	21.97
USMC	Ensemble 1 Hood Down	25.67
ECWCS	Ensemble 9 Hood Down	26.62

Table 29. Lowest three intrinsic evaporative resistances of garments and ensembles based on torso region values

Torso Region		
Garments *not including bottom garments		R_{ecl} (m^2Pa/W)
NAF	Net Undershirt	7.25
ECWCS	Lightweight Undershirt	9.86
SOF	LW Long Sleeve Crew Shirt	12.32
Ensembles *Hood Down Only		R_{ecl} (m^2Pa/W)
ECWCS	Ensemble 8 Hood Down	42.24
USMC	Ensemble 1 Hood Down	44.75
USMC	Ensemble 3 Hood Down	58.80

Table 30. Lowest three intrinsic evaporative resistances of garments and ensembles based on arm region values

Arm Region		
Garments *not including bottom garments		R_{ecl} (m^2Pa/W)
NAF	Net Undershirt	4.74
ECWCS	Lightweight Undershirt	6.52
USMC	Silkweight Undershirt	6.89
Ensembles *Hood Down Only		R_{ecl} (m^2Pa/W)
ECWCS	Ensemble 8 Hood Down	32.21
USMC	Ensemble 1 Hood Down	40.54
USMC	Ensemble 3 Hood Down	44.47

Table 31. Lowest three intrinsic evaporative resistances of garments and ensembles based on leg region values

Leg Region		
Garments *not including top garments		R_{ecl} (m^2Pa/W)
SOF	LW Boxer Briefs	1.88
USMC	Silkweight Drawers	2.91
NAF	Net Underwear	4.54
Ensembles *Hood Down Only		R_{ecl} (m^2Pa/W)
SOF	Ensemble 5 Hood Down	47.66
ECWCS	Ensemble 9 Hood Down	47.66
ECWCS	Ensemble 8 Hood Down	47.89

Tables 24-27 show that SOF Ensemble 3 Hood Down is the only ensemble ranked as one of the three highest R_{cl} for the whole body, torso, arm, and leg regions, indicating a high insulation distributed evenly throughout the ensemble. Tables 28-31 show that the NAF net underwear is the only layer ranked as one of the three lowest R_{ecl} values for the whole body, torso, arm, and leg regions, indicating favorable vapor permeability properties. A caveat of these detailed biophysical evaluations is that they are just one factor that should be considered when deciding which garment, ensemble, or system may be ideal for a given scenario. Ultimately, the biophysical data in this report that includes each layer of a clothing system as well as regional data, provides a more detailed basis for materiel developers to compare the performance of each layer and optimize clothing system design.

A primary motivation for creating the equations described in this report is to predict thermal and evaporative resistances for the variety of ensembles that can be created within each clothing system. These equations are also necessary for implementation of USARIEM's decision aid software [7]. Furthermore, an accurate whole-body resistance value can be calculated from the parallel weighted average of the predicted regional values [19]. To the best of our knowledge, this is the first time equations have been developed to predict whole-body ensemble resistances from the regional values of individual garments. Using regional values as the basis for ensemble prediction is more logical than using whole-body resistance values of garments, due to the possibility of uneven resistances (e.g., high resistances in a single body region and low resistances in the remaining regions) disproportionally affecting prediction results.

The consistently high R^2 of the correlation between the regional sum of garments and ensemble measurements support that it is acceptable to predict ensemble properties from individual clothing items. A possible exception, however was a weak relationship (R^2 = 0.57) between torso evaporative resistance calculated from individual items and the ensemble measurements. One explanation for the weaker correlation might be due to a trapping of moisture between clothing layers and the accumulation of liquid water within each layer when an entire ensemble is configured; a property that isn't fully being accounted for with the individual clothing item tests. Additionally, evaporative resistances for heavy winter clothing are difficult to determine accurately due to the limitations of the current thermal manikin sweating mechanisms. A future test that includes pre and post weighing of the clothing items might help explain this unaccounted error, or more advanced techniques that actually measure water vapor pressure within garment layers could be implemented to answer this question. Fortunately, relative inaccuracies of evaporative resistance measurements do not have a major impact on the prediction outcome of thermoregulatory modeling of cold-weather scenarios, as the prediction outcome is more directly related to thermal resistance input.

CONCLUSIONS

The regional and whole-body biophysical properties of ensembles and garments that are compiled in this report provide a more detailed approach than the traditional reporting of whole-body ensemble values. This detailed database is critical to materiel developers' efforts to optimize the design of cold-weather clothing systems. Equations were derived from this data to predict the regional thermal and evaporative resistances of ensembles from the regional measurements of individual garments. These newly created equations for the torso, arm, and leg regions are rational and more accurate than equations derived from whole-body values [18], as supported by the high R^2 for regional data relationships. This novel approach provides the capability to confidently predict the regional resistances of numerous combinations of cold-weather clothing garments, which can then be calculated into whole-body values if necessary.

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APPENDIX A

PICTURES OF CLOTHING ITEMS

Military Alpine Recce System, U.S. Special Operations Forces (SOF)

Figure 14. Special Operations Forces Lightweight Long Sleeve Crew Shirt (left) and Lightweight Boxer Briefs (right)

Figure 15. Special Operations Forces Midweight Quarter Zip (left) and Midweight Long John (right)

Figure 16. Special Operations Forces Nano Air Hoodie (left) Nano Air Vest (center) Nano Air Bottom (right)

Figure 17. Special Operations Forces Stem Shell Jacket

Figure 18. Special Operations Forces Mixed Range Jacket (left) Mixed Range Pants (right)

Figure 19. Special Operations Forces PneumoFuse Top (left) PneumoFuse Bottom (right)

Figure 20. Special Operations Forces DAS Jacket (left) DAS Pants (right)

Figure 21. Special Operations Forces Helo Parka

Canadian Armed Forces (CAF) cold-weather clothing system

Figure 22. Canadian Armed Forces Thermal Undershirt (left) and Long Johns (right)

Figure 23. Canadian Armed Forces CADPAT Fleece Jacket (left) and CADPAT Fleece Trouser

Figure 24. Canadian Armed Forces CADPAT ICE Jacket (left) and CADPAT ICE Trouser (right)

Figure 25. Canadian Armed Forces CADPAT IECS Parka (left) and CADPAT IECS Bib Pants (right)

Figure 26. Canada Goose Snow Mantra Winter Parka (CADPAT Fleece Trouser are also shown in this picture)

Norwegian Armed Forces (NAF) cold-weather clothing system

Figure 27. Norwegian Armed Forces Net Undershirt and Net Underwear

Figure 28. Norwegian Armed Forces Wool Terry Cloth Undershirt and Wool Terry Cloth Underwear

Figure 29. Norwegian Armed Forces Cotton Field Shirt

Figure 30. Norwegian Armed Forces M/02 Membrane Field Jacket and M/02 Membrane Field Pants

Figure 31. Norwegian Armed Forces M/97 Camouflage Jacket and M/97 Camouflage Trouser

Figure 32. Norwegian Armed Forces Cold Weather Jacket and Cold Weather Trouser

U.S. Army's Generation III Extended Cold Weather Clothing System (ECWCS)

Figure 33. U.S. Army's Generation III Extended Cold Weather Clothing System Lightweight Undershirt (left) and Lightweight Drawers (right)

Figure 34. U.S. Army's Generation III Extended Cold Weather Clothing System Midweight Shirt (left) and Midweight Drawers (right)

Figure 35. U.S. Army's Generation III Extended Cold Weather Clothing System Fleece Jacket

Figure 36. U.S. Army's Generation III Extended Cold Weather Clothing System Wind Jacket

Figure 37. U.S. Army's Generation III Extended Cold Weather Clothing System Soft Shell Jacket (left) and Soft Shell Trouser (right)

Figure 38. U.S. Army's Generation III Extended Cold Weather Clothing System Extreme Cold/Wet Weather Jacket (left) and Extreme Cold/Wet Weather Trouser (right)

Figure 39. U.S. Army's Generation III Extended Cold Weather Clothing System Extreme Cold Weather Parka (left) and Extreme Cold Weather Trouser (right)

U.S. Marine Corps (USMC) cold-weather clothing system

Figure 40. U.S. Marine Corps Silkweight Undershirt and Silkweight Drawers

Figure 41. U.S. Marine Corps Grid Fleece Pullover and Grid Fleece Drawers

Figure 42. U.S. Marine Corps FR Combat Ensemble Blouse and FR Combat Ensemble Trouser

Figure 43. U.S. Marine Corps WindPro Jacket

Figure 44. U.S. Marine Corps Lightweight Exposure Suit Jacket and Lightweight Exposure Suit Trouser

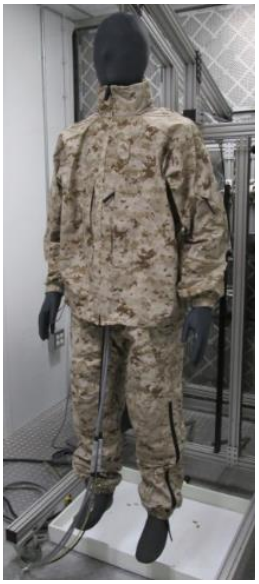

Figure 45. U.S. Marine Corps Extreme Cold Weather Parka and Extreme Cold Weather Trouser

Figure 46. U.S. Marine Corps Snow Camouflage Parka and Snow Camouflage Trouser

APPENDIX B

BACKGROUND ON CLOTHING PROPERTIES

The physical measure of resistance to convection, conduction, and radiation due to clothing is defined by a general clothing property, thermal resistance (R_t) in m^2K/W. Thermal resistance is synonymous with insulation and may be expressed in clo units, with 1 clo equal to 0.155 m^2K/W. The benefit of using clo units is the point of reference to an arbitrary clothing item; a standard men's suit has the approximate insulation of 1 clo.

"The value of [1] clo was selected as roughly the insulation value of typical indoor clothing, which should keep a resting man (producing heat at the rate of 58 (W/m^2) comfortable in an environment at 21°C, air movement 0.1 m/s." (ASTM F1291-16).

Evaporative resistance (R_{et}) is the measure of resistance to evaporative heat transfer due to clothing, with SI units of m^2Pa/W. Although not used in this report, a distinct yet related characteristic, the permeability index, is typically used in conjunction with clo units to describe the clothing's resistance to evaporation.

"An i_m of zero indicates that the clothing system allows no evaporative heat transfer. An i_m of one indicates that the clothing system achieves the theoretical maximum evaporative heat transfer allowed by its insulation." (ASTM F1868-17). For common indoor clothing, the value of i_m is approximately 0.45, although i_m measurements on thermal manikins do not typically exceed 0.60, even for nude manikin measurements.