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EFFECTS OF LAYERING ON THERMAL INSULATION AND VAPOR PERMEABILITY

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EFFECTS OF LAYERING ON THERMAL INSULATION AND VAPOR PERMEABILITY

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14. ABSTRACT

Introduction: Thermal insulation of clothing depends largely on the air trapped between the skin and the clothing layers. Textile from clothing layers and the air between layers provide insulation. The purpose of this work is to examine the effects of layers and air gaps on thermal insulation and vapor permeability. Methods: Standard tests for the thermal and evaporative resistances (Rct and Ret) were conducted (ASTM F1291-16 & ASTM F2370-16) for eight military ensembles within climate controlled environmental chambers. Each of the eight ensembles varied in the types of material and number of layers (2 - 5 layers); while one included a 6th layer in the form of ballistic armor. Results: Thermal insulation (clo) ranged from 1.30 – 2.71 (1.87 ± 0.57), vapor permeability (im) 0.32 – 0.55 (0.41 ± 0.08), and evaporative potential (im/clo) ranged from 0.14 – 0.40 (0.24 ± 0.09). Conclusion: This work provides some quantitative evidence that the thermal insulation is highly dependent on the addition of air layers within clothing ensembles.

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EXECUTIVE SUMMARY

Introduction: Thermal insulation of clothing depends largely on the air trapped between the skin and the clothing layers. Textile from clothing layers and the air between layers provide insulation. Along with insulation, one thick layer or several thinner layers both provide specific benefits of convenience (less layers = less clothing to deal with; more layers = more flexibility for tailored use). The purpose of this work is to examine the effects of layers and air gaps on thermal insulation and vapor permeability.

Methods: Standard tests for the thermal and evaporative resistances (R_{ct} and R_{et}) were conducted (ASTM F1291-16 & ASTM F2370-16) for eight military ensembles within climate controlled environmental chambers. Each of the eight ensembles varied in the types of material and number of layers (2 - 5 layers); while one included a 6th layer in the form of ballistic armor.

Results: Thermal insulation (clo) ranged from 1.30 – 2.71 (1.87 ± 0.57), vapor permeability (i_m) 0.32 – 0.55 (0.41 ± 0.08), and evaporative potential (i_m/clo) ranged from 0.14 – 0.40 (0.24 ± 0.09).

Discussion: The tests showed generally that with the increasing number of layers came increases in thermal insulation and decreases in evaporative potential. No large differences were found between ensembles of similar combined sizes, implying that thermal insulation is provided mostly by the amount of trapped air in an ensemble rather than the number of layers. This is supported by the data comparing Ensemble 4 to Ensemble 8 (Ensemble 4 + body armor); where the additional weight of the body armor compressed the air spaces and thus reduced the thermal insulation while still decreasing the evaporative potential. Vapor permeability depends highly on the type of textile and less dependent on the amount of air space.

Conclusion: This work provides some quantitative evidence that the thermal insulation is highly dependent on the addition of air layers within clothing ensembles.

INTRODUCTION

Thermal insulation of clothing depends largely on the air trapped between the skin and the clothing layers. Textile from clothing layers and the air between layers provide insulation. Along with insulation, one thick layer or several thinner layers both provide specific benefits of convenience (less layers = less clothing to deal with; more layers = more flexibility for tailored use).

Single large coats provides a level of convenience in that only one layer is needed; while layers provide the convenience that the wearer can remove layers if need be, while still staying warm. There is, however, a point where the weight and fit of the layers will start pressing on the wearer squeezing the air out and lowering insulation.

While performing extended outdoor cold weather activities, experts usually agree that the preferred numbers of layers is three: a snug base layer, an insulating layer, and a shell layer. The military once stuck with training the phrase VIP, for vapor, insulation, and protection layers. This layering system is typically best to use when moisture management and wind are important factors to consider. However, there are times, like enclosed spaces (e.g., inside a vehicle or building) where wind and moisture are not as influential and therefore one thick layer could be more protective and practical than several layers.

The purpose of this work is to examine the effects of layers and air gaps on thermal insulation and vapor permeability.

METHODS

Standard tests for the thermal and evaporative resistances (R_t and R_{et}) were conducted [1-2] for eight military ensembles within climate controlled environmental chambers (Table 1; Appendix A). Each of the eight ensembles varied in the types of material and number of layers (2 - 5 layers); while one included a 6th layer in the form of ballistic armor.

Measures obtained for analysis included:

- thermal resistance (R_t) (Eq. 1)
- R_{ct} is converted into units of clo (Eq. 2)
- evaporative resistance (R_{et}) (Eq. 3)
- R_{et} is converted into a vapor permeability index (i_m) (Eq. 4)
- together i_m and clo (i_m/clo) is used to represent the evaporative potential [3-4]

Thermal resistance (R_t) is the dry heat transfer from the surface of the manikin through the clothing and into the environment, mainly from convection; where T_s is surface temperature, T_a is the air temperature in °C or K; Q is power input (W) to maintain the surface (skin) temperature (T_s) of the manikin at a given set point; A is the surface area of the measurement in m^2. Measures of R_t can then be converted to units of clo, where I_T is the total insulation including boundary air layers. Evaporative resistance (R_{et}) is heat loss from the body in isothermal conditions ($T_s \approx T_a$); where P_{sat} is vapor pressure in Pascal at the surface of the manikin (assumed to be fully saturated), and P_a is vapor pressure, in Pascal, of the chamber environment. Measures of R_{et} can then be converted to a vapor permeability index (i_m), a non-dimensional measure of water vapor resistance of materials.

$$R_t = \frac{(T_s - T_a)}{Q/A} \, [\mathrm{m^2K/W}] \qquad \text{Eq 1.}$$

$$1\,clo = 6.45(I_T) \qquad \text{Eq 2.}$$

$$R_{et} = \frac{(P_{sat} - P_a)}{Q/A} \, [\mathrm{m^2Pa/W}] \qquad \text{Eq 3.}$$

$$i_m = \frac{60.6515 \frac{Pa}{°C} R_{ct}}{R_{et}} \qquad \text{Eq 4.}$$

Table 1. Elements included in each ensemble

	Silk-wieght underwear	*Mid-wieght underwear*	*Fleece jacket*	*Soft Shell Jacket and Trousers*	*Lightweight GORE Jacket and Trousers*	*Extereme Cold Weather Jacket and Trousers*	*Interceptor Outer Tactical Vest*
Ensemble 1	Yes	Yes					
Ensemble 2		Yes		Yes			
Ensemble 3	Yes				Yes		
Ensemble 4	Yes	Yes	Yes				
Ensemble 5		Yes		Yes		Yes	
Ensemble 6	Yes	Yes	Yes	Yes			
Ensemble 7	Yes	Yes	Yes	Yes		Yes	
Ensemble 8	Yes	Yes	Yes	Yes		Yes	Yes

RESULTS

Thermal insulation (clo) ranged from 1.30 – 2.81 (1.87 ± 0.57), vapor permeability (i_m) 0.32 – 0.55 (0.41 ± 0.08), and evaporative potential (i_m/clo) ranged from 0.14 – 0.40 (0.24 ± 0.09) (Table 2; Figure 1).

Table 2: Measured biophysical values and trends based on adding layers

					Average values used for analysis, Figures 2 - 4		
	Layers	Insulation (clo)	Permeability Index (i_m)	Evaporative Potential (i_m/clo)	clo	i_m	i_m/clo
Ensemble 1	2	1.30	0.52	0.40	1.45 ± 0.13	0.41 ± 0.10	0.29 ± 0.10
Ensemble 2	2	1.49	0.32	0.22			
Ensemble 3	2	1.55	0.38	0.25			
Ensemble 4	3	1.55	0.55	0.35	1.69 ± 0.10	0.46 ± 0.13	0.28 ± 0.11
Ensemble 5	3	1.83	0.37	0.20			
Ensemble 6	4	1.73	0.36	0.21	1.73	0.361	0.209
Ensemble 7	5	2.81	0.39	0.14	2.81	0.390	0.139
Ensemble 8	6	2.71	0.37	0.14	2.71	0.368	0.136

The tests showed generally that with the increasing number of layers came increases in thermal insulation and decreases in evaporative potential (Figure 1). No large differences were found between ensembles of similar combined sizes, implying that thermal insulation is provided mostly by the amount of trapped air in an ensemble rather than the number of layers. This is supported by the data comparing Ensemble 7 to Ensemble 8 (Ensemble 7 + body armor); where the additional weight of the body armor compressed the air spaces and thus reduced the thermal insulation while still decreasing the evaporative potential. Vapor permeability depends highly on the type of textile and less dependent on the amount of air space.

Graphs using the average or selected values from Table 2 show the polynomial analysis of the trends in the measures of clo (Figure 2), i_m (Figure 3), and i_m/clo (Figure 4).

Figure 1: Measured insulation and evaporative potential compared to number of layers for each ensemble

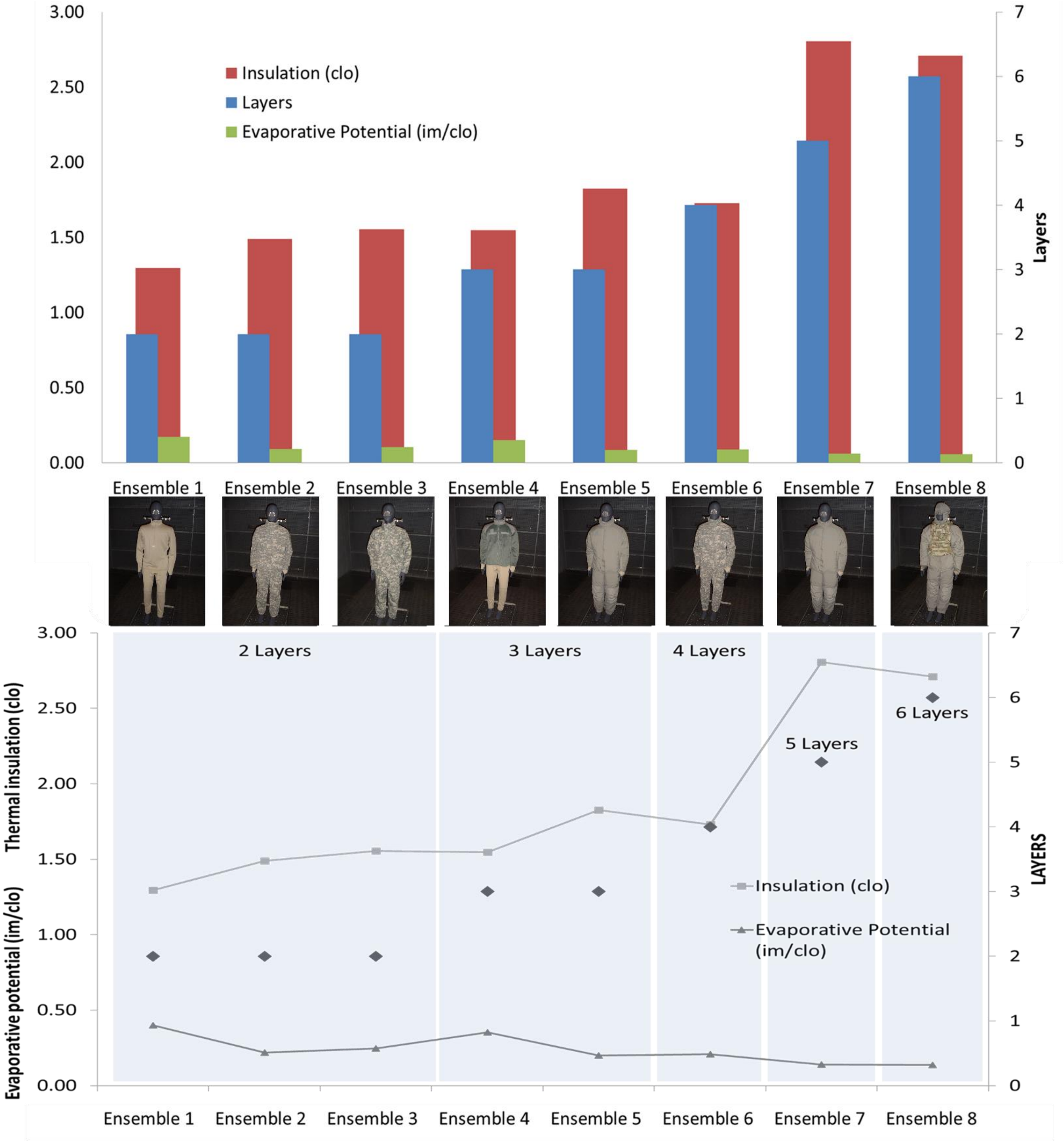


Figure 2. Trending of clo based on layers

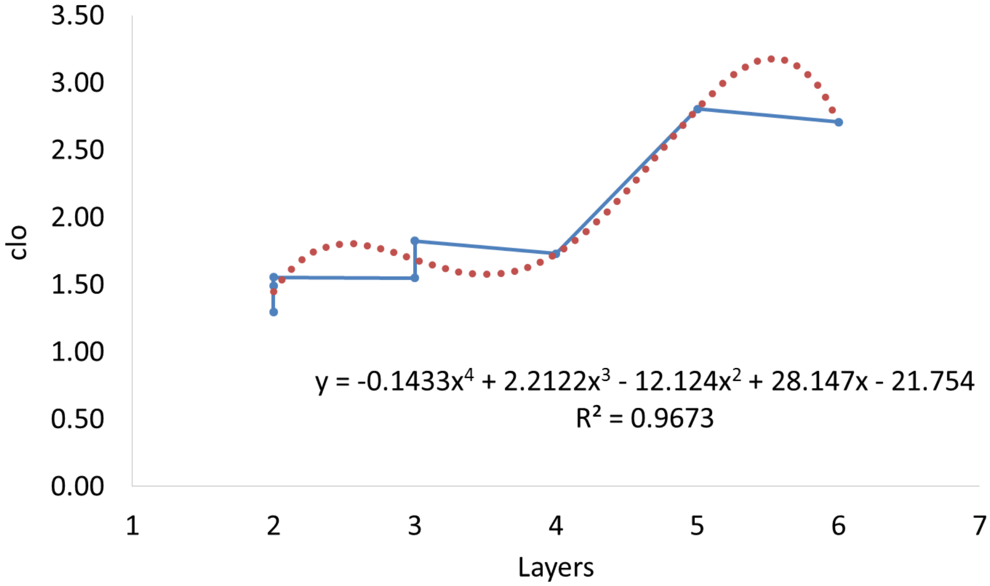


Figure 3. Trending of im based on layers

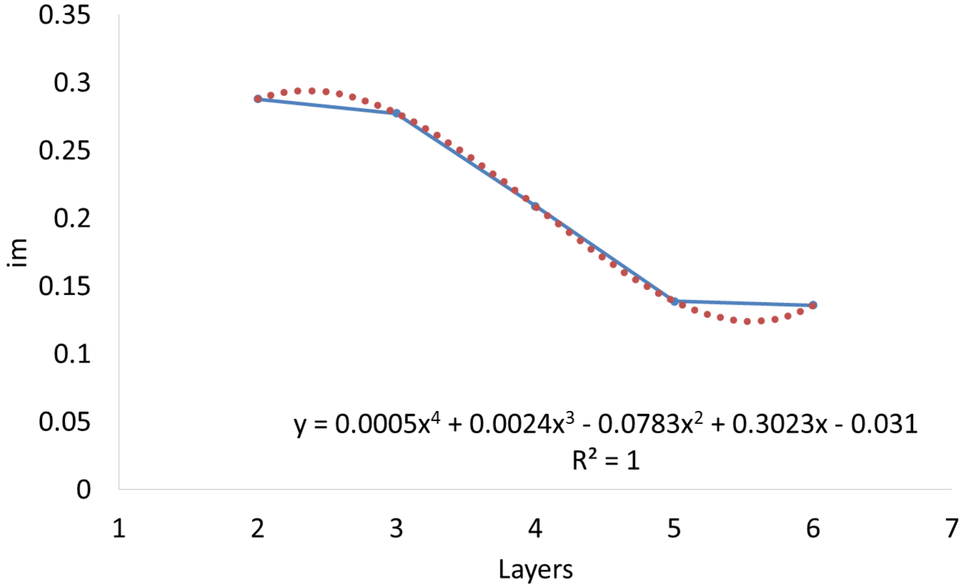
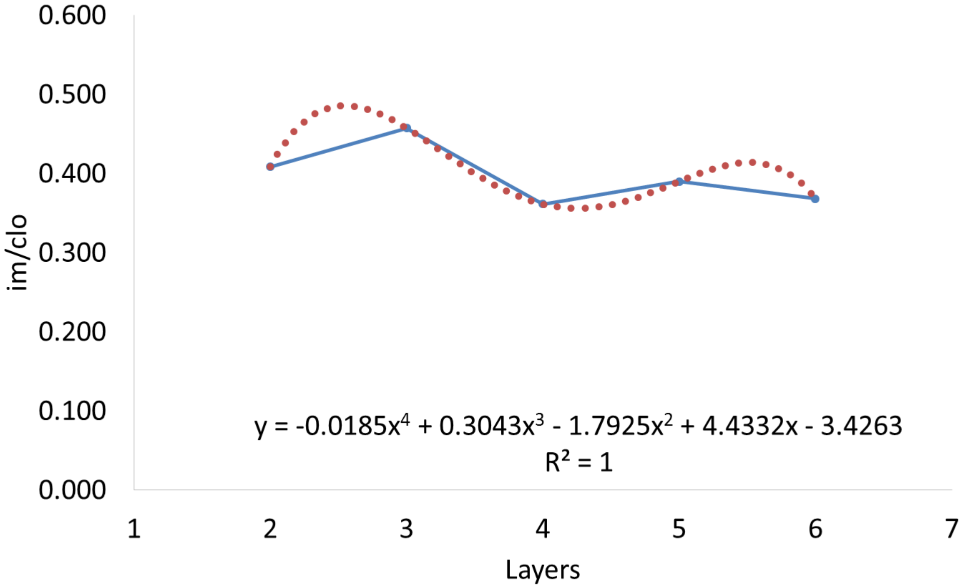


Figure 4. Trending of im/clo based on layers



DISCUSSION

Although studies have shown that thermal insulation eventually stops increasing as more layers are added [5-6], as shown by adding body armor to ensemble 7; this study found a marked improvement in thermal insulation as the number of layers increased to five. Interestingly, an example of why specific testing is important can be seen in the comparison between Ensemble 3 (2 layers) and Ensemble 4 (3 layers) where there is no measured difference in thermal insulation but a 43% improvement in vapor permeability.

Work to better represent the air layers within clothing systems is of significant interest. As demonstrated in this report, the relative air layer plays an influential role in determining the overall resistance value [7]; and therefore the amount of space between each layer is critical for understanding and quantifying total ensemble biophysical values.

This increase in thermal insulation (clo) and decrease in evaporative potential (i_m/clo) has been shown to a lesser degree in analyses specific to body armor systems [8]. While there is still a need for continued work in this area to develop standard testing methods; work specifically focused on estimating or measuring the internal air layer properties of clothing shows promise [9-12].

While some studies have shown the various methods for comparing ensembles based solely on these biophysical measures [13-14]; the use of modeling and analysis methods specific to human physiological response allow for an added benefit to assessing clothing performance [15-18]. Materiel development efforts can benefit from conducting more elaborate trade off analyses to include biophysical assessments, mathematical modeling, as well as some level of human testing [19-23]. Additionally, given the complexity in predicting human responses as they relate to a wide range of environments (solar, terrain, temperatures, etc.) [24-30], activities [31-35], and individual differences [36-42], there should be caution with attempting to generalize test information.

While there are a number of standardized test methods that exist for assessing clothing physical and biophysical properties [1-2, 43-45]; there are also a number of human thermoregulatory models that have become more prevalent for predicting safe limits [46-50] as well as for thermal comfort [49-50]. Many of these models have been validated for particular use cases (e.g., cold, hot, immersion) [21, 51-53]. The main concerns with each of these models is the need for validation with accompanying specific guidance for their proper use, applications, and limitations.

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APPENDIX A. Photos of each ensemble

Figure A. Ensemble 1.

Figure B. Ensemble 2.

Figure C. Ensemble 3.

Figure D. Ensemble 4.

Figure E. Ensemble 5.

Figure F. Ensemble 6.

Figure G. Ensemble 7.

Figure H. Ensemble 8.