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THERMAL RESISTANCE VALUES OF SOME PROTECTIVE CLOTHING ENSEMBLES (U)

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DEFENCE RESEARCH ESTABLISHMENT OTTAWA

TECHNICAL NOTE 91-24

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ABSTRACT

This report describes methods used to predict the thermal insulation values of thin clothing ensembles and compares the results to those obtained from thermal manikin measurements. In calm conditions, the results compare favourably. In windy conditions, the predicted thermal resistance is greater than the measured value. This is because the theory used does not include wind induced ventilation of the clothing and the accompanying increase in heat transfer.

RÉSUMÉ

Ce rapport décrit les méthodes utilisées pour prédire les valeurs d'isolation thermique des ensembles de vêtements légers et compare les résultats à ceux obtenus des mesures d'un mannequin thermique. Dans des conditions calmes, les résultats se compare favorablement. Dans des conditions venteuses, la résistance thermique prédite est plus grande que celle qui fut mesurée car la théorie utilisée n'inclut pas la ventilation (provoquée) des vêtements et l'augmentation du transfert de chaleur qui l'accompagne.

EXECUTIVE SUMMARY

The war with Iraq in the beginning of 1991 sparked renewed interest in the development of new chemical protective garments for the armed forces. Specifically, the military is interested in a clothing ensemble that provides adequate chemical protection without the burden of high heat stress experienced with the current Nuclear, Biological, Chemical (NBC) protective ensembles at high work rates. The high summer temperatures of the Middle East would accentuate the heat stress problems that have been observed during training experiences in the cooler climates of Europe and North America.

In an attempt to meet these concerns, new concepts in protective clothing are being explored. It has been proposed [Farnworth 1983] that tight fitting clothing would alleviate a good deal of the heat stress experienced with current NBC protective ensembles. This concept relies on minimizing the resistance to heat and moisture transport of the clothing ensemble by eliminating trapped air within the clothing. In addition, the thickness and porosity of the fabrics required to give the desired level of protection is under review. This could lead to the use of thinner clothing fabrics, which might enhance both conductive and evaporative heat loss by allowing higher convection and diffusion rates through the garment.

This report describes calculations and measurements of the thermal resistance values of some protective NBC ensembles. These ensembles include the current Canadian Forces (CF) NBC ensemble as well as an experimental, vapour-protective garment developed at Defence Research Establishment Ottawa which will be referred to as the Interim suit. Calculations are based on simple heat transfer models, physical material properties and some experimental observations. Measurements were made on a thermal manikin in both still air and at two wind speeds.

Only thermal resistance was analyzed in this report. Resistance to water vapour transport and its accompanying heat loss by evaporation was not considered. Also, no effort has been made to address the effect of solar radiation or the resistance to solar radiative heat transfer across the clothing. This is an area for which some information is available but which warrants further study. This is particularly true of developing a meaningful experimental protocol to measure the solar radiant heat transfer properties of clothing.

The results of this study show that analytical methods can provide estimates of the thermal resistance of thin clothing ensembles which agree well with measured values, at least for calm conditions. Theoretical results on impermeable surfaces agree well with measurements on the nude manikin both in calm and windy conditions.

When thin, air-permeable garments are exposed to a wind, the analytical method over-predicts the thermal resistance of the ensemble. This is probably due to forced ventilation of the garment and mixing in the internal air layers which results in a higher heat transfer across the air layers. This hypothesis is supported by the closeness of the results obtained from analytical methods and from nude manikin measurements. The thermal resistance of both the Interim and the NBC ensembles was reduced by the same amount in the wind, suggesting that wind induced ventilation of the two garments are quite similar. Further study is required in this area before predictions of the effect of the wind can be made with confidence.

The Interim suit had a lower thermal resistance than the current NBC suit when each was worn alone or with combat fatigues. The thermal resistance of the Interim suit when worn under combat fatigues was approximately the same as that of the NBC garment alone. Some over-garment would be required with the Interim suit if liquid chemical protection was required.

The current NBC garment worn over combat fatigues was found to have a thermal resistance of approximately twice that of the stand-alone Interim suit. In a hot environment where chemical vapour is the only hazard, the NBC suit worn over combat fatigues would cause a much greater heat stress than would the stand-alone Interim suit.

The results presented in this study constitute only a portion of the information required to evaluate the suitability of either the Interim Suit or the current NBC suit. The effect of porosity on evaporative heat transfer and the garments' resistance to solar radiative heat transfer may well be much more important considerations in selecting the most appropriate ensemble. A great deal of work is required both in the theoretical analysis and in the development of meaningful experimental protocols for evaluating clothing involving these additional modes of heat transfer.

1.0 INTRODUCTION

The war with Iraq in the beginning of 1991 sparked renewed interest in the development of new chemical protective garments for the armed forces. Specifically, the military is interested in a clothing ensemble that provides adequate chemical protection without the burden of high heat stress experienced with the current Nuclear, Biological, Chemical (NBC) protective ensembles at high work rates. The high summer temperatures of the Middle East would accentuate the heat stress problems that have been observed during training experiences in the cooler climates of Europe and North America.

In an attempt to meet these concerns, new concepts in protective clothing are being explored. It has been proposed [Farnworth 1983] that tight fitting clothing would alleviate a good deal of the heat stress experienced with current NBC protective ensembles. This concept relies on minimizing the resistance to heat and moisture transport of the clothing ensemble by eliminating trapped air within the clothing. In addition, the thickness and porosity of the fabrics required to give the desired level of protection is under review. This could lead to the use of thinner clothing fabrics, which might enhance both conductive and evaporative heat loss by allowing higher convection and diffusion rates through the garment.

This report describes calculations and measurements of the thermal resistance values of some protective NBC ensembles. These ensembles include the current Canadian Forces (CF) NBC ensemble as well as an experimental, vapour-protective garment developed at Defence Research Establishment Ottawa [Meunier 1991] which will be referred to as the Interim suit. Calculations are based on simple heat transfer models, physical material properties and some experimental observations. Measurements were made on a thermal manikin in both still air and at two wind speeds.

Only thermal resistance was analyzed in this report. Resistance to water vapour transport and its accompanying heat loss by evaporation was not considered. Also, no effort has been made to address the effect of solar radiation or the resistance to solar radiative heat transfer across the clothing. This is an area for which some information is available but which warrants further study. This is particularly true of developing a meaningful experimental protocol to measure the solar radiant heat transfer properties of clothing.

2.0 THEORY

Thin fabrics provide resistance to heat flow by two principle mechanisms. First, the layers of fabric reduce the motion of air adjacent to the fabric, which, due to the low thermal conductivity, k, of air (approximately 0.026 W/mK [Weast 1987]), produces a significant resistance to conductive heat transfer. It has been observed that, as a rule of thumb, clothing layers promote a still air layer with a thickness, ℓ, of approximately 5 mm. The conductive heat transfer coefficient, h_c, for this still air layer can thus be calculated from:

$$h_c = k/\ell = (0.026\ \mathrm{W/mK}) / (0.005\ \mathrm{m}) = 5.2\ \mathrm{W/m^2K} \quad (1)$$

The conductive heat transfer coefficient (which is equivalent to the inverse of the thermal resistance) multiplied by temperature difference across the air layer gives the conductive heat flux across the air layer.

Second, the fabric's radiative properties provide a resistance to heat transfer by thermal radiation. Radiative heat transfer has been found to be a function of temperature to the fourth power, however, for the small temperature differences typically observed in environmental clothing, it is possible to linearize the radiative thermal resistance with respect to temperature. The radiative heat transfer coefficient, h_r, may be calculated knowing the mean temperature, T_m, between the two surfaces exchanging radiant heat and the Stefan-Boltzman Constant, $\sigma = 5.67 \times 10^{-8}\ W/m^2K^4$:

$$h_r = 4\sigma T_m^3 \approx 4(5.67 \times 10^{-8})(300\ K)^3 = 6.1\ W/m^2K \tag{2}$$

The radiative heat transfer coefficient multiplied by the temperature difference between the surfaces gives the radiant heat flux between the surfaces. In this approximation, it has been assumed for convenience that the emissivity of each of the radiating surfaces is one, although most textile fabrics have emissivities of approximately 0.75 [Cain 1986].

The conductive and radiative heat fluxes between fabric layers act in parallel across the trapped air layer and the two heat transfer coefficients noted above may be added together to give an overall heat transfer coefficient:

$$h_a = h_c + h_r = 5.2 + 6.1 = 11.3\ W/m^2K \tag{3}$$

The heat transfer coefficient can be considered to be the inverse of the thermal resistance which then gives a thermal resistance value for the air layer of 0.09 m^2K/W. The thermal resistance is frequently rounded off to 0.1 m^2K/W both for convenience and because varying conditions may violate the above assumptions, changing the thermal resistance slightly. Measured values of thermal resistance of air layers in clothing typically vary between 0.08 and 0.12 m^2K/W.

The effect of wind speed on heat transfer from solid objects such as cylinders and plates is well documented [Özişik 1977]. The thermal resistance of the external boundary layer on clothing can often be predicted using this known data, particularly if the outer fabric has a low air permeability. For natural convection in still air, the Nusselt Number, Nu, (a dimensionless conductive heat transfer coefficient, $h_c d/k$) has been found to depend upon the Grashof Number, Gr, and the Prandtl Number, Pr, two dimensionless quantities relating problem variables, geometry and fluid properties:

$$Nu = c(GrPr)^n \tag{4}$$

where the empirical constants for cylinders and flat plates are evaluated according to the following criteria:

Laminar Flow:	$Gr < 10^9$	$c = 0.59$	; $n = 0.25$
Turbulent Flow:	$Gr > 10^9$	$c = 0.1$	; $n = 0.33$

The Grashof Number in air can be defined as:

$$Gr = g \, \Delta T \, d^3 / T_m \, \nu^2 \tag{5}$$

where g is the acceleration due to gravity (9.8 m/s^2), ΔT is the temperature difference between the clothing surface and the ambient air, d is a length scale defined later and ν is the kinematic viscosity of air (approximately 1.5×10^{-5} m^2/s). The Prandtl Number is the ratio $\mu c_p/k$ which is an expression of the relative rate of diffusion of momentum to the rate of diffusion of thermal energy through the fluid. The Prandtl Number has a value of approximately 0.71 for air.

For Forced Convection, as results form the wind, the Nusselt Number has been found to be a function of the Reynolds Number and the Prandtl Number. It is usual to report the results graphically [Özişik 1977], however, the following relationship has sufficient accuracy for most purposes for Reynolds Numbers in the range of 1000 to 50,000 [Rohsenow 1961]:

$$Nu = 0.26(Re^{0.6})(Pr^{0.3}) \tag{6}$$

The error incurred by using this relationship for Reynolds Numbers up to 100,000 is sufficiently small that this equation can be used for clothing studies in winds up to approximately 20 km/hr. The Reynolds Number may be evaluated as:

$$Re = Ud/\nu \tag{7}$$

where U is the velocity of the wind (m/s).

The above relationships may be used to evaluate the conductive heat transfer coefficient of the outer boundary layer, which when added to the radiative heat transfer coefficient, gives the overall heat transfer coefficient, h_{bl}, of the outer air boundary layer.

The thermal resistance (or equivalently the heat transfer coefficient) of most textile fabrics is typically small due to the fabric's high thermal conductivity (approximately 0.04 W/mK) and to the thinness of most fabrics (typically about 0.5 mm). In most clothing systems, it is of secondary importance compared to the thermal resistance of trapped air layers, however, it may be significant in ensembles which seek to minimize trapped air layers. Its contribution can be calculated as shown in equation 8 using typical numerical values:

$$r_f = \ell_f/k_f = 0.0005/0.04 = 0.0125 \ m^2K/W \tag{8}$$

Once the heat transfer coefficients or thermal resistances for each layer have been determined, the heat flux from the body may be calculated by summing the heat transfer coefficients and multiplying that sum by the temperature difference, ΔT, between the skin and the ambient temperature:

$$q = [\Sigma_i(h_{ai} + 1/r_i) + h_{bl}]\Delta T = h_t\Delta T = \Delta T / r_t \tag{9}$$

where h_t is the overall heat transfer coefficient and r_t is the overall thermal resistance.

As the air permeability of the outer fabric layers increases, the effective conductive thermal resistance of internal air layers is reduced as the air is no longer stationary and mixing is promoted. Detailed practical implications of this have yet to be established and forced ventilation of clothing remains a subject for future research. The air permeability of the outer fabric will be ignored for this report which will lead to greater error for permeable clothing in windy conditions. In calm conditions, a worst case for heat stress considerations, the calculated values of thermal resistance should not be significantly affected by the air permeability of the fabrics.

Also, equation 9 does not include radiant heat transfer due to solar radiation. Including solar radiative heat transfer is conceptually fairly simple, however, it is geometrically and algebraically complex. Since one object of this study was to compare predicted thermal resistances with those measured on a thermal mannikin with no solar radiation, solar radiation heat transfer was not included in the analysis and the radiant temperature of the environment was assumed to be equal to the air temperature.

3.0 ANALYSIS

3.1 Computed Thermal Resistances

The two different protective garments were analyzed in several configurations. The NBC garment was examined as a stand-alone garment, over combat fatigues and in a stand-alone version tailored to be close fitting. The Interim suit was studied both as a stand-alone garment and worn under combat fatigues. These ensembles were analyzed in still air, a 5 km/hr wind and a 20 km/hr wind. A cylinder 1.8 m tall with a diameter of 0.3 m was selected for the theoretical calculations. This height is the same as that of the manikin used in the experimental measurements and the cylinder diameter was selected to give a cylinder surface area of 1.7 m^2, the same as that of the manikin.

For calm air, a natural convection calculation was assumed using a temperature difference of 15°C between the body and the air. The characteristic length, d, for this problem is the height of the vertical cylinder which was 1.8 m. Air properties were evaluated at approximately 30°C which resulted in a value of GrPr of 9×10^9 which is just into the turbulent regime. The turbulent flow constants from Equation 4 yielded a Nusselt Number of approximately 208 which translated into a conductive heat transfer coefficient of 3 W/m^2K (or a thermal resistance of 0.3 m^2K/W). This, when added in parallel to the radiative heat transfer coefficient of 6 W/m^2K and inverted, gave a total thermal resistance for the outer boundary layer of 0.11 m^2K/W in calm conditions.

For the two wind conditions, the thermal resistance of the outer boundary layer was computed using graphical data although Equation 6 could also have been used. In this case, the relevant characteristic length, d, was the diameter of the cylinder. The resulting thermal resistances of the outer boundary layer were 0.1 and 0.04 m^2K/W for wind speeds of 5 and 20 km/hr respectively. When the radiative thermal resistances were added, the thermal resistance between the ensemble outer surface and the environment was found to be approximately 0.06 m^2K/W for a 5 km/hr wind and 0.03 m^2K/W for a 20 km/hr wind.

The current CF NBC garment is made of charcoal impregnated foam with a liquid repellent fabric cotton-nylon shell material. It has a total thickness of approximately 3 mm. Its thermal resistance was measured and found to be approximately 0.07 m^2K/W. It was assumed that nothing was worn under the NBC suit in its stand-alone configuration, although, in the thermal manikin measurements a tight, short-sleeve, cotton T-shirt and briefs where worn. The air permeability of the foam and fabric shell material is approximately 0.0034 m/Pa•s [Osczevski 1991].

The Interim suit is a two-layer, two-piece garment. The inner layer is a very close fitting polypropylene knit approximately 0.5 mm thick. The outer layer is a charcoal impregnated lycra, which has lost much of its stretch because of the impregnating process. While it is not skin tight, it is closer fitting than conventional clothing. The lycra fabric also has a thickness of approximately 0.5 mm. The thermal resistance values determined in Equation 8 was used for these fabrics. In the calculations, it was assumed that there was no air layer under the inner-most garments and an air layer of 2.5 mm existed under the lycra layer. Air permeability for these fabrics is estimated to be approximately 0.021 m/Pa•s [Osczevski 1991].

Combat fatigues use a cotton-nylon fabric with a thickness of approximately 0.5 mm. Again, Equation 8 was used to determine the fabric thermal resistance. The existence of pockets and any reinforcing patches was ignored. The air permeability of this fabric was found to be 0.0037 m/Pa•s [Osczevski 1991].

3.2 Thermal Manikin Measurements

The thermal resistance of the various ensembles was measured on a thermal manikin under calm and light wind (5 km/hr) conditions. Measurements were not made at the higher wind speed due to cost constraints. The manikin was 1.8 m tall with a surface area of 1.7 m^2. The manikin had multiple sections, each heated to maintain a constant surface temperature of approximately 35°C. The difference in temperature between sections was sufficiently small (<0.1°C) that it was deemed unnecessary to weight the temperatures by area. The average thermal resistance of the clothing was computed by multiplying the total surface area by the mean surface temperature and dividing by the total heat supplied to manikin. The room temperature (approximately 20°C) varied between tests but was approximately constant over the course each test. Tests for calm conditions were conducted in a room with normal air circulation.

In every test, the manikin was dressed in the specified garments as well as the CF C4 Respirator, a pair of CF NBC gloves, wool socks, CF combat boots and CF NBC over-boots. For tests with the NBC suit, a short-sleeve, cotton T-shirt and briefs were worn. The T-shirt and briefs were not worn with the Interim suit.

The following five configurations of the garments were tested:

(a) Interim suit;
(b) Interim suit worn under combat fatigues;
(c) NBC suit;
(d) NBC suit worn over combat fatigues;
(e) Tailored NBC suit.

To produce the Tailored NBC suit, the suit was placed on the manikin and excess fabric was gathered and stapled to make the garment tight fitting. This was done to study the effect of minimizing the inner air layer while maintaining all other variables, such as the suit fabric, constant. The manikin was also tested with no clothing to establish benchmark values and to verify theoretical calculations of the thermal resistance of the outer boundary layer.

4.0 RESULTS AND DISCUSSION

The results of the theoretical analysis and the thermal manikin measurements are shown in Table 1. Under still air conditions, the predicted and measured values are quite similar and the practical implications of the differences are small. The very close agreement between theory and measurements for the nude manikin supports the theory for the boundary layer contribution to thermal resistance for garments of impermeable fabrics in the wind and for calm conditions.

Table 1. Results of the analytical predictions and experimental measurements of the thermal resistance (in metric units of m^2K/W) of NBC protective ensembles.

Ensemble Name	Calm Air		5 km/hr Wind		20 km/hr Wind	
	Predicted	Measured	Predicted	Measured	Predicted	Measured
Interim	0.23	0.21	0.19	0.13	0.16	-
Interim and Fatigues	0.34	0.29	0.29	0.19	0.27	-
NBC Suit	0.28	0.31	0.24	0.21	0.21	-
NBC and Fatigues	0.39	0.36	0.35	0.25	0.32	-
Tailored NBC	0.22	0.26	0.18	0.18	0.15	-
Nude Manikin	0.11	0.11	0.06	0.05	0.03	0.03

The thermal resistance of the Interim suit is approximately one-third less than that of the current NBC suit. Much of the difference is likely due to the reduction in the thickness of trapped air layers but a not insignificant amount can be attributed to the reduction in thickness of the fabric. It should be noted that the Interim suit alone is not intended for use against liquid chemicals. Some of the thickness of the current NBC foam material was intended to address the threat of a liquid drop in close proximity to the charcoal layer on the liquid-repellent shell material, however, the NBC suit has additional specifications requiring increased levels of protection.

When the garments are exposed to wind, the differences between theory and measurement increase for all ensembles but the tailored NBC suit. The theoretical and measured thermal resistances for the tailored suit were identical which may be fortuitous or due to elimination of wind-induced ventilation of the NBC garment.

If the internal air gap under the NBC garment is eliminated by tailoring, the wind would have nowhere to flow if it penetrates the fabric. Lateral resistance to air flow within the foam would be much greater than transverse resistance due to the larger quantity of fabric which the air must traverse in the lateral or circumferential direction. This should hold true for any garment which is very tight fitting. Thus, a truly skin tight garment may produce a higher heat stress than a similar, but slightly loose garment when the wind is blowing.

The results in the wind show a significant reduction in the resistance to heat loss for both the NBC suit and the Interim suit in both configurations. In fact, the reduction in all cases was approximately 0.1 m^2K/W which exceeds the theoretically predicted reduction of 0.05 m^2K/W for the outer boundary layer on an impermeable surface. This suggests that both the Interim and NBC garments are ventilated at approximately the same rate by the wind.

Some research on heat transfer due to forced ventilation through the clothing fabric has been performed [Seddigh 1983], however, further work is required before calculations of forced ventilation and its accompanying heat transfer can be applied confidently in a wide variety of conditions.

5.0 CONCLUSION

The results of this study show that analytical methods can provide estimates of the thermal resistance of thin clothing ensembles which agree well with measured values, at least for calm conditions. Theoretical results on impermeable surfaces agree well with measurements on the nude manikin both in calm and windy conditions.

When thin garments which are very air-permeable are exposed to a wind, the analytical method over-predicts the thermal resistance of the ensemble. This is probably due to forced ventilation of the garment and mixing in the internal air layers which results in a higher heat transfer across the air layers. This hypothesis is supported by the closeness of the results obtained from analytical methods and from nude manikin measurements. The thermal resistance of both the Interim and the NBC ensembles was reduced by the same amount in the wind, suggesting that wind induced ventilation of the two garments was quite similar. Further study is required in this area before predictions of the effect of the wind can be confidently made.

The Interim suit had a lower thermal resistance than the current NBC suit when each was worn alone or with combat fatigues. The thermal resistance of the Interim suit when worn under combat fatigues was approximately the same as that of the NBC garment alone. Some over-garment would probably be required with the Interim suit if liquid chemical protection was required.

The current NBC garment worn over combat fatigues was found to have a thermal resistance of approximately twice that of the stand-alone Interim suit. In a hot environment where chemical vapour is the only hazard, the NBC suit worn over combat fatigues would cause a much greater heat stress than would the stand-alone Interim suit.

The results presented in this study constitute only a portion of the information required to evaluate the suitability of either the Interim Suit or the current NBC suit. The effect of porosity on evaporative heat transfer and the garments' resistance to solar radiative heat transfer may well be much more important considerations in selecting the most appropriate ensemble. A great deal of work is required both in the theoretical analysis and in the development of meaningful experimental protocols for evaluating clothing involving these additional modes of heat transfer.

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