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DEFENCE RESEARCH ESTABLISHMENT OTTAWA
REPORT NO. 998

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Environmental Protection Section
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Abstract

The concept and theoretical considerations of a clothing system for cold weather is discussed. The temperature range of interest was -40 to 10°C which was divided into an extreme-cold temperature range (-40 to -10°C) and a cold wet temperature range (-10 to 10°C). An essential goal of the clothing system was to provide adequate thermal insulation for metabolic rates between 150 and 600 W while a desirable goal was to provide adequate thermal insulation for metabolic rates up to 1000 W. The clothing differs from conventional clothing mainly in its doctrine of use as insulation is added to or remove from the outside. This makes the clothing more versatile and more easily used.

Résumé

Le concept et les considérations théoriques entourant la sélection d'un système de vêtements pour les températures froides sont discutés. L'échelle de températures d'intérêt s'étend de -40°C à 10°C et ceci est divisé en deux conditions: extrêmement froide (-40 à -10°C) et froid-mouillé (-10 à 10°C). Le but essentiel du système de vêtements était de fournir une isolation thermique adéquate pour des taux métaboliques variant de 150 à 600 W et, si possible, de fournir une protection adéquate pour des taux métaboliques allant jusqu'à 1000 W. Ces vêtements diffèrent des systèmes conventionnels principalement au niveau de la doctrine d'utilisation puisque le degré d'isolation thermique est ajusté en ajoutant ou en enlevant des épaisseurs à partir de l'extérieur. Cette alternative rend les vêtements plus versatile et plus facile à utiliser.

Executive Summary

This report describes the theoretical and laboratory work done in the development of a cold weather, environmental clothing system for use by the Canadian Forces. The prototype garments consist of an outer parka, winter combat jacket, and winter combat trousers for the cold-wet environment and the addition of a polyester-pile jacket and trouser liners and a thick pair of outer trousers for the extreme-cold environment.

The clothing was designed to allow a soldier to remain thermally comfortable while working by wearing one of several, easily-changed configurations of the clothing system. It is intended that the configuration worn be chosen so that the insulation provided would be suitable for both the activity level and the ambient temperature at which the soldier is working. Ideally, the clothing should be capable of providing the correct amount of insulation over the entire range of metabolic rates (150 to 1000 watts) and ambient temperatures (-40 to 10°C). In order to take advantage of the versatility of the system, the user must adopt the doctrine of adding insulation to, and removing insulation from, the outside.

A mathematical model was used to predict thermal insulation requirements for the clothing and to predict optimum insulation distribution over the body. The predictions of the thermal insulation provided by prototype garments were compared with experimental test results obtained with the clothing on a heated manikin. There was good agreement for the whole body thermal resistance, but there were differences for some individual body regions and in the wind.

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1.0 Introduction

This report documents the theoretical and laboratory work performed in the development of a cold weather, environmental clothing system for use by the Canadian Forces (CF). The report outlines the design objectives for the clothing, explains the reasoning behind various physiological and physical assumptions that were made and lists other considerations which were incorporated into the clothing system. The report describes the set of prototype garments which were constructed and the results of preliminary manikin tests which were used to establish the accuracy of the theoretical predictions of the thermal insulation provided by prototype garments.

The mathematical model used in this report to predict thermal insulation requirements of clothing was kept simple, incorporating only major variables. Quite elaborate mathematical models of the insulation provided by clothing have been proposed [Newburgh (1968)], but they are difficult to apply due to their complexity. In industry, clothing design is often based upon tradition, fashion and state-of-the-art materials rather than the fundamental physics of clothing requirements.

The literature contains a number of physiological investigations of the effects of wearing or using various items of clothing and equipment [Lotens (1986b), Goldman (1974,1986)]. These factors seem to be of secondary importance compared with the physiological differences between individuals, the variations in the physiological responses of an individual from day to day and differences in the fit of the garments between individuals. Differences of 25% in the insulation provided by identical clothing systems for different individuals have been reported [Newburgh (1968)]. In light of these difficulties, the use of a complex model does not seem justified, although the information obtained from these investigations can be used as guidelines.

The prototype garments were designed to allow a typical soldier to remain thermally comfortable while working by wearing one of several, easily-changed configurations of the clothing system. It is intended that the configuration worn would be chosen such that the insulation provided would be suitable for both the activity level and the ambient temperature at which the soldier is working . Ideally, the clothing should be capable of providing the correct amount of insulation over the entire range of metabolic rates and ambient temperatures of the design domain. Practical considerations limit the clothing's performance to discrete bands. Garments should be designed such that these bands of constant thermal insulation provide as much versatility in the clothing system as is convenient. A fundamental characteristic of the clothing system is that it should allow the wearer to be able to easily adjust the clothing to prevent overheating or cooling.

The prototype system developed in this report makes use of some current items of CF clothing (mostly handwear and footwear) even though the analysis indicates that some of these items may be inadequate, or at least not an optimum choice. Improvements in these items lie outside the scope of the present work and remain subjects for future research.

The clothing configurations specified in this report are recommended configurations only. Individuals should use these as guidelines and adjust the clothing to meet their specific thermal requirements as they vary their activity level or as the ambient temperature changes.

2.0 Design Criteria

2.1 General Considerations

Moisture transport through clothing worn for cold environments is a slow process. Sweating into the clothing is therefor not a very effective way to remain thermally comfortable and results in wet clothing. The soldier must therefore take other measures to prevent overheating and sweating. The current CF doctrine to avoid over-heating in winter clothing is to use multiple, removable layers of clothing and to ventilate the clothing as required. Unfortunately, the current CF clothing system is not sufficiently versatile to meet this doctrine for the range of activities and climates encountered by the CF soldier. Since other requirements of current and future protective clothing may minimize or preclude ventilation, it should not be relied upon to prevent over-heating.

The prototype clothing system outlined in this report will follow the multiple layer concept while attempting to avoid the need for ventilation. This is not to say that the possibility of venting should be precluded, only that it is viewed as a secondary, fine tuning mechanism that may be used to enhance the basic system when conditions permit. The design concept of this clothing borrowed heavily from the clothing designs of the Inuit yet it differs as it attempts to address the additional requirements of the CF soldier both in the extreme-cold and the cold-wet environments. Earlier studies [Osczevski (1981)] laid the groundwork for producing more versatile clothing than the traditional Inuit clothing by using modern materials.

The insulation provided by the garments in the prototype clothing system is arranged so that the layer nearest to the skin has little thermal insulation. Subsequent clothing layers have increasingly larger thermal resistances. In the clothing system, insulation is generally added to or removed form the outside of the body to keep the soldier thermally comfortable. This allows rapid, convenient adjustment of the clothing and permits significant changes in the amount of thermal insulation worn without unduly exposing the wearer to the environment. This is important when working in adverse environments where changing activity levels require substantial changes in the amount of insulation worn in order to remain thermally comfortable.

An ideal clothing system would be capable of allowing the soldier to work under any set of environmental conditions and at any metabolic rate physically possible. Recognizing that this is not currently practical, one is forced to select the best clothing system which is feasible. In its minimal configuration the clothing system should allow the wearer to work at the maximum design work rate and at the maximum design ambient temperature without sweating or becoming cold to a significant extent. In its maximal configuration, the clothing system should allow the wearer to be comfortable at the lowest design activity rate and ambient temperature. The objective is to give the clothing sufficient versatility that the wearer can work at a large number of intermediate activity levels and ambient temperatures. This could be accomplished by using a large number of similar layers of clothing which could be removed or added as required, however, this is again an impractical solution. Studies indicate [Lotens (1986a)] that energy expenditures for a task increase approximately 4% for each layer of clothing worn. Thus, the number of layers of clothing should be kept to a minimum.

For layered clothing to be versatile and easily used, each layer of clothing should be suitable as an outside layer. Liquid water in the environment is not generally a problem in the extreme-cold but it can pose a formidable challenge to a soldier's health in a cold-wet environment as recently noted in a report of the Falkland Islands conflict [McCaig (1985)]. If garments are to be useful in both environments, then the outer surface of each clothing layer should be water-proof. To aid in drying, these layers should also be water-vapour permeable.

It is generally desirable to prevent the wind from penetrating the clothing although controlled ventilation would increase the versatility of the clothing. To prevent wind penetration through the clothing, the outer shell of exposed garments must be wind-proof. Also, adequate closures must be provided at all openings to prevent wind from bypassing the wind- proof shell.

Several products are currently available which are both wind and water-proof, yet water-vapour permeable. The product with which most people are familiar with is Gore-tex. There are now several competitors in the commercial market of which Dermoflex and Stedthane are two current Canadian alternatives. All of these materials may be applied to most clothing fabrics. Two problems with these materials have been noted: when cold, the water-vapour transport through these materials is quite low and removal of sweat by diffusion through them is not a practical solution to the problem of heat stress; when these materials are applied to a textile fabric, the resulting fabric is stiffer and noisier.

2.2 Environmental Assumptions

It was decided to design the clothing system for the temperature range of -40 to 10°C. Current military clothing is acceptable above 10°C and temperatures lower than -40° C are encountered infrequently. The clothing can be used at other temperatures, however, it is most versatile when used within the above temperature range.

The temperature range has been somewhat arbitrarily divided as two problem areas had been identified by the military. A cold-wet range was defined, extending from 10°C to -10°C; an extreme-cold range was defined, extending from -10°C to -40°C. This division allowed a more practical clothing system to be developed; one which shared most garments between each temperature range.

The garments used in either temperature range should be designed so that they function adequately between approximately -5°C and -15°C to provide additional versatility in the complete system.

In the mathematical model used to compute the amount of thermal insulation provided by each garment, the outer surface of the clothing was specified to be at ambient temperature. This is equivalent to assuming a high heat transfer coefficient at the outer surface which is typical when a wind is blowing over the clothing. This wind was assumed not to penetrate into the clothing. Solar heating was not included in the calculations.

2.3 Physiological Assumptions

Metabolic rates can vary from approximately 70 W during sleeping to more than 2000 W for very short durations of extremely hard work [Auliciems (1973)]. For the purposes of discussion, the definitions of work intensity in terms of metabolic rate shown in Table 1 were adopted. Selecting a range of metabolic rates (or activity levels) as design criteria is also somewhat arbitrary. The limits of what is realistically or physically attainable by the clothing should be considered when making this choice.

Resting individuals require so much insulation, even in moderately cold conditions, that it is not currently feasible to provide clothing which is effective in this situation and which can be used at higher metabolic rates. Sleeping bags, heated shelters or avoiding extended periods of low activity are the only current practical solutions.

Most military activities fall between light and heavy heavy work intensities [Allen (1973), Auliciems (1973), Goldman (1974), Osczevski (1981a)]. It was therefore decided that the essential goal of the clothing system would be to allow the soldier to work comfortably at a large number of metabolic rates in the range of 150 to 600 W. Recognizing that the soldier may be required to work harder, a desirable goal of providing for work rates up to 1000 W was adopted.

Table 1. Definition of Work Intensity in Terms of Total Metabolic Rate [Astrand (1977)].

Work Intensity	Metabolic Rate (watts)
resting	80
light	<175
moderate	175 to 350
heavy	350 to 525
very heavy	525 to 700
extremely heavy	>700

The thermal resistance of the clothing was chosen so as to maintain, as closely as possible, the soldier in a comfortable if not thermally-neutral state. Thus, it was assumed that the soldier does not sweat nor does he vaso-constrict appreciably for the duration of a given task. At the end of that task, the soldier would take steps to alleviate any discomfort by adjusting layers of clothing, work rate or both.

Vaso-constriction results in the reduction of blood supply to the extremities, virtually eliminating the heat supply to the hands and feet. Although the physiological conditions for which vaso-constriction occurs are not fully understood, if the whole body cools, vaso-constriction will occur. Increasing the thermal insulation around the hands and feet only serves to decrease the rate of cooling but will not prevent cold injury unless other measures are taken to restore the blood flow [Vanggaard (1988)]. Thus, in order to prevent vaso-constriction, the insulation requirements of both the extremities and the body as a whole must be considered.

Although man's body temperature is often quoted as 37°C, this is a typical core body temperature which varies even under normal conditions. It has been found that a comfortable average skin temperature is approximately 33°C but slightly lower average skin temperatures (approximately 31°C) may be acceptable while exercising [Livingstone, Newburgh (1968)]. Lower local skin temperatures may be deemed comfortable [Newburgh (1945)]: arm and leg temperatures may lie between 30 and 32°C; foot and hand temperatures may lie between 24 and 32°C. Since the hands and feet represent only a small fraction of the total body surface area, a comfortable skin temperature of 33°C will be adopted for this report and it will be assumed that this skin temperature exists over the whole body.

Not all of the energy produced by metabolic processes is dissipated as heat through the clothing: a sizable quantity of energy can be lost through respiration; some fraction of the energy goes to performing external work.

Heat loss from respiration can be estimated if the following variables are known: the breathing rate; the difference between the ambient and respired air temperatures; and the difference between the ambient and respired air humidity. Breathing rates vary from approximately 0.1 l/s at rest to 1.5 l/s for very heavy work [ASHRAE (1972)] with a maximum rate of approximately 3 l/s for the highest work rate attainable [Bell (1954)]. In cold climates, the inspired air will generally include only small quantities of water vapour even though it may be fully saturated. Some researchers [Newburgh (1968)] suggest that the expired air is fully saturated and at a temperature close to the core temperature while others believe that it is not saturated and can be substantially lower than the core temperature.

A survey of the literature failed to find any detailed experimental results relating the respired air temperature to both activity and ambient temperature. Some data do exist for respired air temperature as a function of ambient temperature while the subject is at rest [Webb (1951)] and for various breathing rates with different ambient temperatures but again at rest [McFadden (1982)]. Recent experiments [Cain (1988)] suggest that for moderate work rates the expired air is close to saturation but that its temperature is slightly less than the body core temperature. It was observed that the expired air was approximately 28°C when the ambient air temperature was -40°C, while for ambient temperatures near 0°C, the expired air temperature was approximately 32°C. In the theoretical model, the expired air was assumed to be saturated at 30°C. The rate of energy loss from the body associated with respiration under these conditions was found to represent approximately 15% of the total metabolic energy production rate.

The working efficiency of the body is difficult to determine for many activities but it appears to vary from near zero when resting to a maximum of approximately 25% under ideal conditions. This efficiency is the fraction of the metabolic rate which produces useful external work. Since very few efficiencies were found in the literature, it was assumed that the efficiency for a working person was 15%.

The heat loss through the clothing was calculated as the the total metabolic rate less both the respiratory heat loss and the external work done. By simply relating the respiratory heat loss and the body's efficiency to the metabolic rate as in the previous discussions, the heat loss through the clothing can be calculated as 70% of the total metabolic rate.

The calculation of the thermal resistance of various garments requires an estimate of the dimensions of the various regions of the body which are to be insulated. For this study, the body was divided into the following general regions: torso, arms, legs, feet, hands and head. Numerical calculations of the insulation provided by various clothing garments were performed for those fitting a person 1.85 m tall, weighing 85 kg. For such an individual, Dubois' empirical formula [Dubois (1916)] predicts that the total body surface should be approximately 2.1 m^2. The individual surface areas of each body part were estimated using the following fractions of the total body surface area: Torso, 0.35; Legs, 0.32; Arms, 0.14; Head, 0.07; Feet, 0.07; Hands, 0.05 [Newburgh (1949)]. Dimensions assigned to the various body regions may be found in Table 2.

A person is capable of working for short periods of time at rates which do not maintain thermal neutrality. This results in either an thermal energy debt or surplus for the body. The tolerance of the body to such a debt or surplus will depend upon the body mass and psychological factors but it has been suggested [Goldman (1974)] that a thermal energy debt of 300 kJ represents a limit beyond which the risk of injury becomes significant. The criteria of 20% wetted skin and an energy surplus of approximately 100 kJ are quoted as threshold comfort levels but it is not indicated whether these conditions are related or if they are independent. Others [Kuno (1956)] suggest that a 100 kJ energy surplus would be accompanied by a significant amount of sweating. For this report, it will be assumed that an energy debt of 300 kJ or an energy surplus of 100 kJ are acceptable variations from thermal neutrality.

Table 2. Body Data Used In Calculating Thermal Resistances
[1] The radius is that of a cylinder of the given length and lateral surface area.

Body Region	Area m^2	Length m	Radius[1] m
torso	0.74	0.75	0.156
legs	0.67	0.75	0.071
arms	0.29	0.55	0.043
feet	0.15	0.30	0.039
head	0.15	0.25	0.094
hands	0.11	0.20	0.042
Total Area	2.1		

If it is assumed that a person accrues an energy debt over the time which a given metabolic rate may typically be sustained, then a tolerance of 300 kJ is equivalent to a variation of approximately 10% of the the metabolic rate. For example, assume a person can sustain a metabolic rate of 1000 W for 1 hour and remain thermally neutral. If the person loses 300 kJ in excess of that to remain thermally neutral during that hour, then this represents 83 W or, approximately, a 10% variation on the basic 1000 W metabolic rate. For a 100 kJ energy surplus a similar argument results in a 3% variation of the basic 1000 W metabolic rate.

This tolerance simplifies the clothing design considerably as now a finite number of clothing configurations can be specified which can produce the thermal resistances required to cover the range of activity levels and ambient temperatures where before the theory required an infinite number of ensembles.

2.4 Calculation of the Clothing Thermal Resistance

The thermal insulation provided by thin layers of fabric is a result of two mechanisms: reduction of both conductive and radiative heat transfer. As air has a low thermal conductivity, it is a good barrier to conductive heat transfer provided the air is motionless. Layers of fabric trap air, restricting its motion.

The resistance to conductive heat transfer will depend upon the motion of the air and the thickness of the air spaces within the clothing. Fabric layers can also reduce radiative heat transfer from the body by reflecting and absorbing thermal radiation. The amount of radiative thermal resistance provided will depend upon the construction of the clothing and the material properties of the fabrics used. It has been found that, as a rule of thumb, a single layer of common clothing fabric can have a thermal resistance of approximately 0.10 m^2K/W [Farnworth]. This thermal resistance includes both conductive and radiative contributions.

Insulating battings behave in much the same way as single layers of fabric, however, a smaller quantity of material is required to achieve the same thermal insulation with battings than with fabric layers. This is a result of two processes. First, even a low density batting has sufficient fibre volume to minimize convection of air within its boundaries. Thus, the region of still air in the batting can be much thicker than that next to a single fabric layer of the same mass per unit area. This results in an appreciable reduction in conductive heat transfer. Second, thermal radiation heat transfer is reduced due to the larger number of multiple reflections between and absorption at the batting fibres as opposed to a single reflection and absorption for a single fabric layer.

The thermal insulation obtained from either layers of fabric or a batting can be significantly reduced if the wind can penetrate through the materials. Also, water in the clothing can increase energy loss by evaporation and, in extreme cases, by increased conduction. As previously noted, when calculating the heat loss through a garment, it was assumed that the garment was dry and there was no wind penetration. The final clothing design must ensure that these assumptions are met if the theoretical calculations are to be valid. As these attributes are generally desirable for health and comfort reasons, this seems to be a reasonable restriction for the model and a desirable goal for the clothing.

The thermal resistance of a garment is the temperature difference across the garment divided by the heat flux across the garment:

$$R = (T_i - T_o) / Q \qquad (1)$$

which can be interpreted on a whole body, a portion of a body or on a unit area basis as is convenient. When calculating the thermal resistance obtained from a given thickness of insulation, the surface area and hence the surface geometry can be important.

For this study, the body was modeled as an assembly of cylinders whose characteristics are noted in Table 2. It was assumed that heat transfer occurred on the lateral surfaces of the cylinders only; no heat was lost from the ends of the cylinders.

The thermal resistance obtained by wrapping a cylinder with an insulating layer can be calculated from:

$$R = \frac{\ln(1 + x/a)}{2\pi k L} \qquad (2)$$

where it is assumed that the thermal conductivity of the material is the same whether it is in either a cylindrical geometry or flat plate geometry (which is the usual configuration for measuring the thermal conductivity of materials).

When the thickness of the material, x, is small relative to the cylinder radius, a, equation 1 can be approximated by the equation for thermal resistance in a flat plate geometry:

$$R = x / A K \qquad (3)$$

As the insulation thickness increases, the difference between results obtained from equation 2 and equation 3 increases. Equation 3 over-predicts the actual value of insulation by 25% when the insulation thickness is approximately one half the cylinder radius. The question then arises as to whether the geometry of the human body is better modeled as a collection of cylinders or slabs. Since much of the clothing considered in this report is thick, the cylindrical representation is more appropriate and equation 2 was used.

The thermal conductivity of insulating battings is a function of both the batting structure and its temperature [Farnworth (1985)]. For battings of large-diameter, polyester fibres such as those used for Polarguard, the thermal conductivity is approximately 0.05 W/mK at 0°C and 0.065 W/mK at 30°C [Dent (1984)]. The values of thermal conductivity used in the theoretical model for footwear and hand wear were: 0.029 W/mK for the duffle socks of the CF mukluks [Nolan (1976), Dent (1984)]; 0.016 W/mK for leather combat boots and gloves [Baumeister (1959)].

The final calculation of the thermal insulation of prototype garments was based on thickness measurements from the actual garments. Loose fitting garments were assumed to have a 5 mm layer of still air beneath them. Battings and shell fabrics had a thermal conductivity of 0.05 W/mK (corresponding to an average temperature of 0°C) except in the manikin tests. For the manikin tests, where the average clothing temperature was 30°C, the batting and shell material thermal conductivity was 0.065 W/mK. Tight-fitting garments such as socks were considered not to have a still air layer trapped beneath them so the thermal resistance of these items was due solely to the thickness of the material itself.

3.0 Analysis and Results

Figure 1 graphically depicts the range of metabolic rates and ambient temperatures in which the clothing system must operate. The area enclosed by both the broken and solid lines represents the desired range while the area enclosed by the solid lines only represents the essential range of metabolic rates at which a soldier should be capable of working while wearing the clothing.

A clothing configuration of fixed thermal resistance can be represented as a linear relationship between heat loss through the clothing and the temperature difference across the clothing as shown in equation 1. The solid, inclined lines in Figure 1 represent a series of desirable thermal resistances obtainable from a clothing system. The intervals between the solid lines represent the acceptable variation from thermal neutrality. Various configurations of a single clothing system can be used in both regimes but at differing metabolic rates for different ambient temperatures: the clothing which is suitable for a soldier working very hard (675 W) in a very cold environment (- 40°C) is also suitable for the soldier who is doing moderate work (215 W) in a more moderate environment (10°C). This simplifies the clothing system as most garments can be used in both regimes.

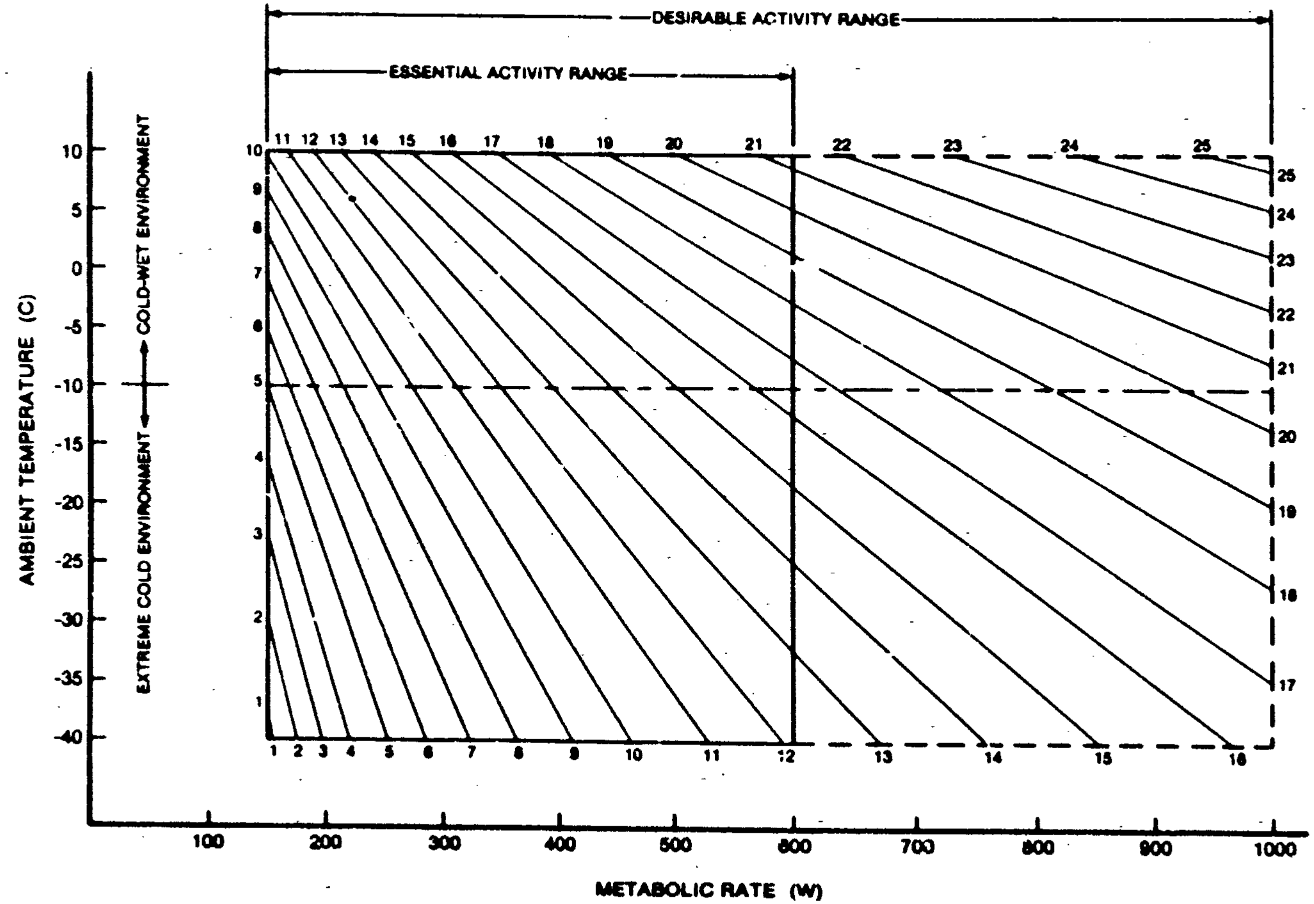

Figure 1. Design domain for the cold weather clothing system. The box bounded by the solid lines on the left encloses the essential goals of the clothing system while the area enclosed by the broken lines to the right represents the desirable goals for the clothing. The inclined lines represent hypothetical clothing configurations of constant thermal resistance. The values of the thermal resistance corresponding to the indices of this figure are given in Table 3.

Table 3. Average Thermal Resistance Of A Clothing System Which Would Satisfy The Insulation Requirements For The Entire Design Domain.

Index	Thermal Resistance K/W
1	0.71
2	0.63
3	0.56
4	0.49
5	0.44
6	0.39
7	0.34
8	0.30
9	0.27
10	0.24
11	0.21
12	0.19
13	0.16
14	0.15
15	0.13
16	0.11
17	0.10
18	0.085
19	0.075
20	0.065
21	0.058
22	0.051
23	0.045
24	0.040
25	0.036

From Figure 1, a clothing system would require at least 25 configurations to obtain the required insulation values to cover the entire design domain. The numerical values of the average thermal resistances, with the indices corresponding to those in Figure 1, are given in Table 3. Unfortunately, it is physically very difficult to provide clothing which has a thermal resistance of less than 0.1 K/W in calm conditions which can still provide protection under other, more severe conditions. This means that the last several configurations are unattainable in a purely passive system in which ventilation and sweating are not viable means of energy loss.

3.1 Optimum Insulation Distribution

An analysis of the clothing insulation requirements for thermal neutrality was made in which the mass of insulation was minimized. It was assumed that the only variables affecting the mass of the systems were the thicknesses of the insulation on the various regions of the body.

It was found that the torso should have the greatest thickness of insulation followed by the head, legs, arms, hands and feet, however, the difference between the maximum and minimum insulation thickness was only 10%. This is a small difference in the insulation thickness and, to a first approximation, it could be said that the body should be covered with a uniform thickness of insulation to minimize the required mass of insulation. Unfortunately, some garments such as gloves and boots are subject to practical limits on thickness and it may be impractical to try to have the same thickness of insulation on the extremities as is on the torso.

Three hypothetical clothing assemblies were also analysed to determine the effect of varying the insulation density and thermal conductivity. Two battings were used: one, a low density, 11 kg/m^3, high thermal conductivity, 0.045 W/mK (Polarguard); and the other, a high density, 21 kg/m^3, low thermal conductivity, 0.039 W/mK (Thinsulate C). In two assemblies, the insulation was entirely of one batting or the other. In the third assembly, a combination of the battings was used: the torso, arms and hands insulated with the low density batting; the head, legs and feet insulated with the high density batting.

The insulation for the assembly of entirely low density batting weighed the least; the assembly of combined batting weighed approximately 20% more than the low density batting for the same amount of thermal insulation; the high density batting assembly weighed approximately 50% more than the low density batting assembly. The thickness of the low density batting assembly was 15 to 20% greater than that of the high density batting assembly with similar results for the mixed batting assembly. The thermal resistance obtained for each region of the body was only marginally different in all three cases. It was decided that a difference in thickness of 20% for most garments would not be significant but a weight increase of 50% would probably be undesirable. For these reasons, the lower density batting was employed where feasible.

3.2 Garment Selection For The Prototype Clothing System

A prototype clothing ensemble was designed which attempted to meet the insulation values in Table 3 and yet remain practical. A description of this system is given in Table 4. Tradeoffs between performance, practicality, simplicity and user preference were required. Additionally, commercially available fabrics were used which restricted the choice of insulation thicknesses.

For the outer parka, the winter combat jacket and trousers, a flame-retardant, Dermoflex coated nylon was chosen as the outer shell material to give a wind-proof, water-proof yet water-vapour permeable outer surface. The outer trousers were made of a tightly-woven nylon as it was not thought that they would be used in the cold-wet. A 270 gm/m^2 Polarguard batting was selected for the insulation in the outer parka and trousers as it requires few quilt lines. For additional fire protection and comfort, a light Nomex liner was included in the winter combat jacket and trousers.

The ensemble for the cold-wet climate clothing consists of 11 articles of clothing: outer parka; winter combat jacket; shirt; face mask; winter combat trousers; socks; combat boots; combat gloves; combat glove liners. These items allow a selection of overall thermal resistances which cover a reasonable portion of the cold-wet design limits. The outer trousers, although not included here in the cold-wet system, would increase the useful range of the clothing significantly.

The clothing for extreme-cold climates requires the addition of only three garments to provide substantial coverage for the extreme-cold environment along with the substitution of the mukluks for the combat boots and arctic mitts for the combat gloves. The additional garments are polyester pile jacket and trouser liners which are worn beneath the winter combat jacket and trousers, and thick pair of outer trousers. These liners are not generally intended to be worn as exterior garments as they have neither a wind-proof nor a water-proof outer layer. The decision to make these items inner garments was contrary to the general design philosophy of adding insulating layers over other garments, but it was felt that a third wind-proof and water-proof layer

Table 4. Selected Clothing Items For Prototype construction. Values are calculated assuming a thermal conductivity of 0.05 W/mK.

Item	Description
Torso	
a) Outer Parka	- 3.5 cm of low density fibrous batting with a wind-proof, water-proof, vapour-permeable outer surface; intended to be worn at the lower work rates; no pockets. R = 0.82 K/W
b) Combat Jacket	- Wind-Proof, water-proof, vapour-permeable shell with a light lining (1-2 mm) for comfort. Principle working outer garment for the torso. R = 0.19 K/W
c) Shirt	- Light-weight (1 mm). R = 0.17 K/W
d) Liner	- 5 mm polyester pile. Insulation supplement for use in the extreme-cold. R = 0.28 K/W

Item	Description
Head	
a) Outer Parka Hood	- 3.5 cm polyester batting with similar construction to outer parka. R = 9.42 K/W
b) Combat Jacket Hood	- 2 mm. Similar construction to the combat jacket. R = 1.90 K/W
c) Liner Hood	- 5 mm Polyester pile. Similar construction to the liner for the torso. R = 1.36 K/W
d) Toque/Face Mask	- 2.5 cm Polyester batting with a wind-proof, water-proof, vapour-permeable shell. For use in both the cold-wet and extreme-cold. R = 6.00 K/W
Legs	
a) Outer Trousers	- 3.5 cm Polyester batting with a Wind-Proof, water-proof, vapour-permeable; no pockets. R = 0.84 K/W
b) Combat Trousers	- Wind-Proof, water-proof, vapour-permeable; light liner (1-2 mm); intended as principal outer working garment. R = 0.21 K/W
c) Trousers Liner	- 5 mm lightweight, flexible polyester pile. Insulation supplement for the extreme-cold environment. R = 0.30 K/W

Item	Description
Arms	
a) Outer Parka Arms	- 3.5 cm Polyester batting with similar construction to the torso. R = 1.62 K/W
b) Combat Jacket Arms	- Similar construction as for the torso. R = 0.48 K/W
c) Shirt	- Similar construction as for the torso. R = 0.41 K/W
d) Jacket Liner Arm	- Similar construction as for the torso. R = 0.68 K/W
Feet	
a) Socks	- Conventional cotton, nylon or wool socks as preferred. R = 0.46 K/W (2 mm); 1.15 K/W (5 mm)
b) Combat Boots	- Current issue leather boots. For the cold-wet environment. R = 0.13 K/W
c) Mukluk	- Current CF issue with wool duffle sock (10 mm) and insoles. R = 2.45 K/W

Item	Description
Hands	
a) Combat Glove	- Current CF issue for cold wet. R = 1.00 K/W
b) Combat Glove Liner	- Current CF issue for the cold wet. R = 0.55 K/W
c) Arctic Mitts	- Current CF issue for the extreme-cold. R = 2.61 K/W

would make the clothing system too stiff, although this was never verified experimentally. Also, the shell fabric required for outer layers is more costly than other conventional fabrics. Thus a

compromise was made on these garments. It must be stressed that these garments are intended for use in extreme- cold only and are not recommended for use in cold-wet climates. British troops operating in a cold-wet environment found that, when working, the thermal underwear and their outer garments provided too much insulation and removing the thermal underwear was not feasible in the field [McCaig (1986)]. This is especially true of the pile trouser liner although the pile jacket liner would also be difficult to remove when worn with military webbing.

The densely-shaded regions of Figure 2 show the predicted coverage of the design domain for the prototype system in it most convenient configurations. The lightly-shaded regions indicate portions of the design domain which are less conveniently covered by the clothing. It can be seen that, although the prototype system does not meet the extremes of the design limits, it does cover a large fraction of the area within the design limits.

The thermal resistance of the cold-wet configurations of the clothing system varies between 0.09 and 0.13 K/W. Including the outer trousers greatly increases the amount of the design area covered (up to 0.26 K/W) but the extremes of the design limits are still unattained. In the high temperature and metabolic rate region, sweating will occur. This is probably true even if some of the clothing can be removed or ventilated. More insulation would be required at the lower metabolic rates, particularly on the legs. Additional insulation could be added either to the outer parka or the outer trousers, however, the penalties would be increased weight and bulk for these garments. The cold-wet configuration without the outer trousers should allow approximately 25 minutes of work at a metabolic rate of 150 W at -10°C before becoming undesirably cold; approximately 1.5 hours would be possible under the same conditions if the outer trousers are included in the system.

The thermal resistance of the extreme-cold configurations, varies from approximately 0.17 to 0.38 K/W. This does not provide adequate insulation for the lower metabolic rates at low temperatures for extended lengths of time and it provides too much insulation at high metabolic rates and temperatures. The system can be extended to provide more coverage at the higher metabolic rates if the pile jacket and trouser liners are removed, although this is somewhat inconvenient to do quickly or without shelter. Again, in order to extend the clothing's thermal insulation to cover the lower metabolic rates, more insulation would be required.

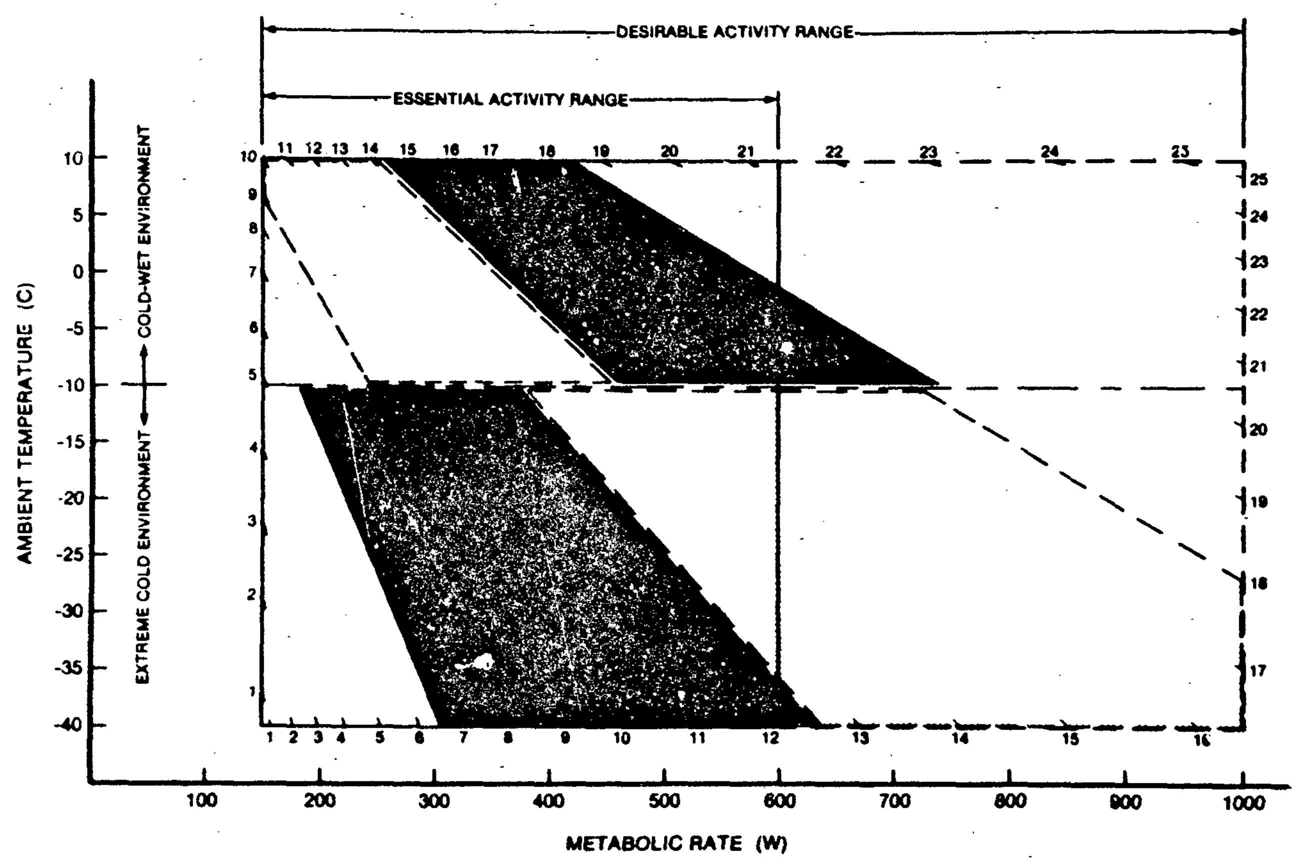

Figure 2. Predicted prototype clothing capabilities. The densely-shaded regions indicated the range of metabolic rates and ambient temperatures for which the prototype clothing system can provide appropriate and easily changed levels of thermal insulation. The lightly-shaded regions indicate levels of thermal resistance which the clothing can provide although changes in the clothing configuration are less convenient. These results assume no ventilation or sweating.

With the current level of insulation, the clothing should allow approximately 1 hour of work at -40°C and 150 W.

The weight of the prototype clothing is comparable to the current CF clothing in both the cold-wet and the extreme-cold configurations. Comparing the two systems is complicated since certain garments in one system have no equivalent garment in the other (such as the insulated outer trousers of the prototype clothing). It was found, that the prototype clothing weighed slightly less than the current CF clothing for the cold-wet environment. In the extreme-cold configuration, the current CF clothing weighed less than the prototype clothing, with much of the difference in weight attributed to the outer trousers in the prototype clothing.

Most of the garments in the prototype clothing system are shared between the cold-wet and extreme-cold configurations. This is not the case for the CF cold weather clothing. If all of the clothing required for the temperature range of -40 to 10°C is considered as a single system, there is a considerable saving with the prototype clothing system both in the total number of garments required and the total weight of the system.

If the outer trousers could be carried practically and the user could be convinced to use them in the cold-wet environment, then this ensemble could be also be used as a rough sleeping system. Though this is not generally recommended, it may be operationally advantageous under certain conditions. The clothing would need to be augmented with a bivi-sac and a sleeping pad which provides approximately 2 cm of insulation when compressed under body weight.

Foam sleeping pads typically have a thermal conductivity of approximately 0.04 W/mK [Osczevski (1981b)]. A 2 cm thick pad would provide a thermal resistance of about 0.5 K/W below the body. In its maximum cold-wet configuration, the clothing system worn in conjunction with a foam pad/bivi-sac should provide a thermal resistance of approximately 0.6 K/W above the body and approximately 0.75 K/W below the body for an overall thermal resistance of approximately 0.33 K/W. This should allow for extended periods of sleep at approximately 10°C (assuming a metabolic rate of 85 W with with 15 W lost through respiration). This configuration would provide only 1 hour and twenty minutes of sleep at -10°C before the sleeper became undesirably cold. In an extreme-cold environment, there would be not be sufficient insulation to give the user a significant amount of rest.

3.3 Thermal Manikin Tests of the Prototype Clothing

The prototype clothing system was made to the specifications noted in Table 4 and thermal insulation values were measured on a stationary, heated manikin [Potter (1988)]. Table 5 and Appendix A summarize the results of the calculations and experimental tests to determine the thermal resistance of the prototype clothing.

In the tests, a heated manikin was clothed and allowed to come to steady state. Tests were performed both in still air and in a simulated 20 km/h wind. In the wind tests, the manikin was facing into a highly turbulent wind which was created by a large fan. In all tests, all closures were securely fastened, however, insufficient information was obtained to determine how effective the closures were. The first three tests reported here included a face mask with openings for the eyes and the nose and mouth while the last two tests had no face mask. The ambient temperature was approximately 25°C and the manikin skin temperature was maintained at approximately 33°C.

The dimensions of the manikin were slightly smaller than those assumed in the calculations. The torso surface area was significantly less than assumed in the model (0.49 as opposed to 0.74 m^2). Also, because of the construction of the manikin, approximately 10% of the area of the manikins' legs was included in the torso in the theoretical model.

Table 5 lists the overall predicted and experimentally determined thermal resistances for the prototype clothing in several configurations. The results compare reasonably well for the cases of still air but some differences do appear in the simulated wind cases. Examining the local values of thermal resistance, presented in Appendix A, shows that the theory and experiment agree in most cases reasonably well but that there are some significant differences in some instances.

There was good agreement between theory and experiment for all of the handwear tested, but the theoretical predictions of thermal resistance for footwear was greater than that which was measured. For the combat boots, this may have been caused by compression of the sock inside the boot thereby reducing the thermal resistance of the sock. Predictions for the mukluk and sock significantly over-estimated the thermal resistance measured (30 to 40%), much more than can be explained by compression of the insulation. It is possible that the assumed thermal conductivity of the wool duffle socks (0.03 W/mK) was overly optimistic. The thermal resistance predicted for the insulation on the arms was good in most cases with still air however in tests with wind, the experimentally determined thermal resistance was substantially less than that predicted. This was also seen in the torso and head insulation predictions which may indicate wind penetration into the outer parka and to a lesser extend into the winter combat jacket. Further tests are required to determine whether these discrepancies are in fact due to wind penetration of the clothing or whether some other assumption is inappropriate.

Table 5. Theoretical and Experimental Values of Thermal Resistance for Prototype Garment Assemblies. Thermal conductivity of battings vere corrected for an average temperature of 30°C to match experimental conditions. An external still air layer was added to the theoretical values obtained to obtain still air conditions. A 20 km/h simulated wind was used in the noted tests. For further details see Appendix A.

Ensemble Thermal Resistance (K/W)

	Still Air		Simulated Wind	
Test	Theory	Experimental	Theory	Experimental
A	0.24	0.24	0.18	0.16
B	0.30	0.35	0.25	0.20
C	0.40	0.41	0.35	0.25
D	0.14	0.18	0.068	0.086
E	0.18	0.26	0.084	0.11

Although manikin tests are much simpler to perform than physiological evaluations, detection of events such as wind penetration into the clothing is harder to determine unless the manikin has a large number of small zones for measuring heat loss. The conclusions drawn from a set of manikin tests must be carefully considered since minor adjustments such as the addition of a scarf around the neck or the tightening of a drawstring around the face may significantly reduce any ventilation of the clothing. Unlike a human test subject, a manikin is rarely able to indicate which particular adjustment needs to be made during the course of an experiment.

4.0 Conclusion

A theoretical analysis indicates that it should be technically feasible to produce a practical clothing system which is more versatile than that currently available to the Canadian Forces. A prototype clothing system was designed which relies on several layers which can be easily adapted to meet the soldiers' insulation requirements in either rapidly changing activity levels or environmental conditions. In order to take advantage of the versatility of the system, the user must adopt the doctrine of adding insulation to, and removing insulation from, the outside. Ventilation was not included as the system may be required to function under conditions where ventilation is not possible or is minimal. In conditions where ventilation is possible, the clothing can be opened somewhat to permit ventilation.

The configurations of the prototype clothing system provided appropriate levels of thermal insulation to cover most of the area within the essential goals (150 to 600 W metabolic rate) and much of the area within the desired goals (150 to 1000 W) for the temperature range of -40 to 10°C, although it failed to attain the extremes of the design limits. It would be possible to increase the thermal insulation of the system to achieve the low work rate and low ambient temperatures regions, but the penalties would be increased weight and bulk for the clothing. The high temperature and high work rate regions can be attained in the extreme-cold environment (-40 to -10°C) with some inconvenience but in the cold-wet environment (-10 to 10°C) it is predicted that the clothing would provide too much insulation if a wind and water-proof barrier is maintained.

Experimental tests on a heated manikin showed some differences from predicted thermal resistances, particularly in the wind. Agreement for whole body thermal resistance was good but individual body regions showed some notable discrepancies. Wind penetration into the clothing through the closures may have been partially responsible for the differences in the simulated wind tests, however, further tests are required to verify this.

Under certain conditions, the clothing system, along with a bivi-sac and sleeping pad, could function as a rou n sleeping system. This is only feasible for the cold-wet environment. For the extreme-cold environment, the amount of sleep obtainable is predicted to be less than an hour.

Appendix A. Details of the comparison between predicted and experimentally determined thermal resistance values for prototype garments in various configurations. Batting material conductivity has been adjusted to 0.065 W/mK to match the mean clothing temperature (30°C) of the test conditions.

Thermal Resistance (K/W)

Test	Body Region	Still Air Theory	Still Air Experiment	Simulated Wind Theory	Simulated Wind Experiment	Configuration Description
A	Hands	3.52	3.33	2.61	2.32	Shirt, Jacket Liner, Combat Jacket, Combat Trousers Liner, Combat Trousers, Arctic Mitts, Heavy Socks, Mukluks, Face Mask, Combat Jacket Hood.
	Feet	3.76	2.64	3.09	1.90	
	Arms	1.91	1.67	1.57	1.00	
	Legs	0.66	0.70	0.51	0.49	
	Torso	0.78	1.11	0.64	0.73	
	Head	2.71	2.05	1.35	1.17	
	Total	0.24	0.24	0.18	0.16	
B	Hands	3.52	3.65	2.61	2.67	Shirt, Jacket Liner, Combat Jacket, Outer Parka, Trousers Liner, Combat Trousers, Arctic Mitts, Heavy Socks, Mukluks, Face Mask, Combat Jacket Hood, Outer Parka Hood.
	Feet	3.76	2.77	3.09	2.05	
	Arms	3.16	2.84	2.82	1.62	
	Legs	0.66	0.92	0.51	0.50	
	Torso	1.41	2.02	1.27	1.02	
	Head	4.36	3.53	3.62	1.69	
	Total	0.30	0.35	0.25	0.20	

Thermal Resistance (K/W)

Test	Body Region	Still Air Theory	Still Air Experiment	Simulated Wind Theory	Simulated Wind Experiment	Configuration Description
C	Hands	3.52	3.75	2.61	2.64	Shirt, Jacket Liner, Combat Jacket, Outer Parka, Trousers Liner, Combat Trousers, Outer Trousers, Arctic Mitts, Heavy Socks, Mukluks, Face Mask, Combat Jacket Hood, Outer Parka Hood.
	Feet	3.76	2.60	3.09	1.76	
	Arms	3.16	2.90	2.82	1.84	
	Legs	1.50	1.39	1.35	0.87	
	Torso	1.41	2.16	1.27	1.24	
	Head	4.36	3.47	3.62	1.68	
	Total	0.40	0.41	0.35	0.25	
D	Hands	1.91	1.91	1.00	0.92	Shirt, Combat Jacket, Combat Trousers, Heavy Socks, Combat Boots, Combat Gloves, Combat Jacket Hood.
	Feet	1.87	1.62	1.20	1.13	
	Arms	1.23	1.42	0.89	0.80	
	Legs	0.36	0.51	0.21	0.27	
	Torso	0.50	0.86	0.36	0.38	
	Head	1.60	1.48	0.24	0.50	
	Total	0.14	0.18	0.068	0.086	

Thermal Resistance (K/W)

Test	Body Region	Still Air Theory	Still Air Experiment	Simulated Wind Theory	Simulated Wind Experiment	Configuration Description
E	Hands	1.91	2.16	1.00	0.88	Shirt, Combat Jacket, Outer Parka, Combat Trousers, Heavy Socks, Combat Boots, Combat Gloves, Combat Jacket Hood, Outer Parka Hood.
	Feet	1.87	1.66	1.20	1.13	
	Arms	2.48	2.75	2.14	1.46	
	Legs	0.36	0.66	0.21	0.32	
	Torso	1.13	1.92	0.99	0.62	
	Head	1.62	3.09	0.26	0.77	
	Total	0.18	0.26	0.084	0.11	

Glossary

a	Cylinder Radius, m
A	Surface Area, m^2
k	Thermal Conductivity, W/mK
R	Thermal Resistance, K/W
T	Temperature, °C or K
x	Insulation Thickness, m
π	Pi, 3.14159

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The concept and theoretical considerations of a clothing system for cold weather is discussed. The temperature range of interest was -40 to 10°C which was divided into an extreme-cold temperature range (-40 to -10°C) and a cold-wet temperature range (-10 to 10°C). An essential goal of the clothing system was to provide adequate thermal insulation for metabolic rates between 150 and (?)0 W while a desirable goal was to provide adequate thermal insulation for metabolic rates up to 1000 W. The clothing differs from conventional clothing mainly in its doctrine of use as insulation is added to or removed from the outside. This makes the clothing more versatile and more easily used.

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