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# System Design of Cold Weather Protective Clothing

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**ABSTRACT**

System design of cold weather protective clothing is a critical process, as it involves consideration of the effects of a number of external and internal parameters like environmental factors and physical, physico-mechanical and psychological parameters. The bulk and weight of the textile materials used in protective clothing should be as low as possible, so that clothing does not create physical stress and discomfort to the soldier and does not affect his combat duties adversely. This paper discusses the essential factors involved in the designing of cold weather protective clothing and different insulating materials available in the market for developing better protective clothing. Different stores developed at the Defence Materials & Stores Research & Development Establishment, Kanpur, the order of arrangement of various insulating materials in those stores and the protection level achieved are discussed.

## 1. INTRODUCTION

The primary function of cold weather protective clothing is to protect the individual from the natural environment. For civilians, the designing of protective clothing is simple, as the only requirement is protection against cold, whereas for military personnel and soldiers of other paramilitary forces, besides thermal insulation, a number of other requirements are also important. These include: ease of handling combat and operational hazards, accomplishing their mission with the clothing on their body, protection against rain, snow ingress and extreme conditions of cold and wind. All the above requirements have to be met by the protective clothing and at the same time the wearer should not feel any discomfort. Generally, the high level of protection expected in a cold weather protective clothing may result in clothing which exerts considerable physical stress on the wearer. Hence, design and development of protective clothing is very critical, as it involves selection of appropriate textile materials and strategy for their use individually and collectively, so that the protective clothing causes minimum physical stress on the wearer, while the individual would be effectively protected from cold and can attend his combat duties effectively.

Wool and woollen pile fabric have been the oldest materials used for providing protection against cold since ancient times. After the invention of synthetic fibres, utilisation of acrylic fibres and polyester fibres in different forms was exploited for use in making cold protective clothing. Systematic and extensive studies on wool, acrylic pile and polyester batting revealed that polyester batting has good insulation/ weight ratio against extreme cold and this makes polyester batting one of the important constituents in protective garments, where weight of the garment is of prime concern, especially

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for protective clothing used in glacier and Siachin regions. Researches have been carried out to develop new and effective synthetic insulating materials to provide protection against cold. As a result, several synthetic insulating materials have been developed by different fibre manufacturers.

Selection of material for cold weather protective clothing is done with particular focus on minimising heat loss from the body to the environment, so that the metabolic heat generated from the body is not lost to the environment and instead keeps the body warm. Simultaneously, the material should allow evaporation of sweat from the body to the environment. If the clothing prevents evaporation of sweat to the environment, sweat gets accumulated on the skin and gives a feeling of discomfort to the wearer. In extreme cold conditions, the sweat gets frozen and can cause frostbite. Thus, two properties, viz., minimum heat loss and sweat evaporation, are very important. These are primarily governed by two important factors: (i) thermal insulation of the material, and (ii) moisture vapour permeation.

The performance characteristics of clothing assemblies are often characterised by these two factors. Design and development of cold weather clothing, therefore, requires an understanding of these two parameters.

## 2. THERMAL INSULATION

The thermal insulation of a material depends on many physical parameters like (i) thermal conductivity of the material, (ii) thickness of the material, (iii) density of the fibre, (iv) temperature of outside environment, (v) heat transfer coefficient of external air, and (vi) air space between the skin and the material. Thermal insulation is a measure of thermal protection provided by a material against cold.

Thermal insulation of a fabric surface is determined by measuring heat flux in unit time from unit area of the surface.

Since air is a good thermal insulator, the insulation of air ($I_a$) is defined as[1]

$$I_a = (T_c - T_a)/H$$

where, $T_c$ is the temperature at the surface of the clothing; $T_a$, air temperature; and H, heat flux through the clothing surface.

Resistance to heat flow is primarily determined by the amount of air entrapped inside the layers and the flow of outside air at the outer surface of the clothing. If the amount of entrapped air is high, the material will provide better insulation against passage of heat, sound and electricity. However, water molecules replace air trapped in the interstices and reduce insulation effect of the material due to higher thermal conductivity of water[2]. When thermal insulation increases, the external thermal load through the cloth decreases. This external thermal load is related to sweating through the clothing[3].

### 2.1 Thermal Insulation Measurement Technique

Thermolabo-II thermal tester, developed by Prof Kawabata of Japan, is an advanced instrument for determining thermal insulation value (TIV). The instrument works on the same principle on which hot plate method is based. The electricity consumed in wattage to maintain specific temperature of hot plate with the fabric sample is compared with the wattage consumed in maintaining the same temperature as that of the hot plate without the sample and the ratio is expressed in percentage[4].

Four techniques are available for making these measurements: (i) dry contact in which the fabric sample is placed in direct contact with the hot plate, (ii) dry spacer in which the sample is placed 5 mm away from the hot plate, (iii) wet contact in which a wet filter is placed between the hot plate and the sample, and (iv) wet spacer in which a wet filter is placed 5 mm away from the specimen. The purpose of the wet technique is to simulate sweating body condition.

### 2.2. Correlation

Thermal insulation is also measured in terms of 'clo' value which is determined using the following expression[5]:

$$I_{cl} = I_{total} - I_{air}$$

$$I_{total} = \frac{(MST - T_{air}) \times 0.18}{H}$$

where, $I_{Cl}$ is the insulation of the clothing ensemble (in clo); $I_{total}$, insulation of the clothing ensemble and air; $I_{air}$, insulation of air (which is 0.6 clo at an air velocity of 70 ft/min); MST, mean skin temperature; $T_{air}$, air temperature in the cold room; and $H$, total non-evaporative heat loss.

The unit 'clo' is defined as 1 clo = 0.18 °C/ k cal/sq m /hr. 1 clo unit of thermal insulation will maintain a resting-sitting man, whose metabolism is 50 k cal/sq m/hr, indefinitely comfortable at 21 °C, relative humidity less than 50 per cent and air velocity[6] movement of 20 ft/ min. It is roughly equivalent to the thermal insulation provided by a business suit with the usual undergarments. The Defence Materials & Stores Research & Development (DMSRDE), Kanpur, has developed differents types of ECW clothing. A typical example is the jacket with waist coat and trousers. The jacket and trousers are made of three layers of fabric having the outermost layer of nylon, a middle layer of polyester batting and the innermost layer of acrylic pile fabric. The 'clo' value of such a system measures 2.4. The two inner layers help in entrapping air and providing increased warmth to the wearer.

Most of the materials lose their insulation properties under wet conditions. Down-feathers, supposed to be the best thermal insulating material, lose their insulation properties under wet conditions. This is due to higher heat loss in water compared to air: heat loss in water is 25 times higher than in air at the same temperature. This is an important factor to be considered while designing protective clothing.

## 3. MOISTURE VAPOUR PERMEATION

Excessive sweating due to physical activity causes progressive reduction in thermal insulation due to condensation of sweat, which eventually wets the cloth and when the temperature is low enough, i.e., sub-zero range, it may lead to frostbite. So, the clothing assembly should be capable of allowing the evaporation of water vapour and at the same time should be able to prevent water entering into the fabric. In practice, a compromise is required to be struck between these requirements, so that the water is kept out while perspiration is transmitted, so as to retain heat. Dry air is a relatively poor conductor of heat, whereas addition of water molecules in air greatly increases convective heat loss.

Moisture vapour permeability (MVP) is the ability of the fabric to allow sweat and moisture vapours to pass through it. This is determined by measuring the moisture permeability index which is a measure of the resistance of clothing to passage of water vapours.

The open disk method for measuring water vapour transmission is satisfactory for measuring breathability, but if the air gap is more than 1 cm, similar results are obtained on all fabric. Sweating hot plate method is also used for studying the combined heat and water vapour flow through the clothing under transient conditions[7].

MVP is essential in cold weather clothing to allow perspiration through the skin to dissipate itself. MVP depends on clothing construction (weave) and the fibre materials. Perspiration from the skin decreases with increase in vapour pressure. When the ambient humidity rises, the fabric picks up moisture and the amount of moisture is determined by the relative humidity and temperature. Moisture affects the thermal conductivity of the material. With increase in moisture content, the thermal conductivity increases[8] (Fig.1).

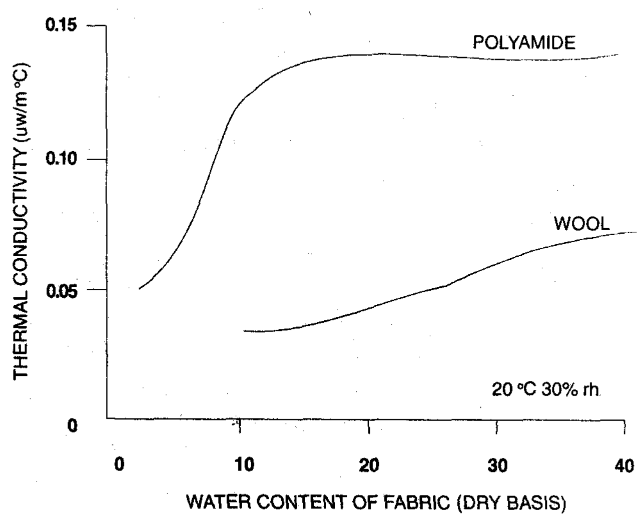


**Figure 1. Effect of moisture content on thermal conductivity**

## 4. INFLUENCE OF MOISTURE CONTENT ON THERMAL CONDUCTIVITY

Thermal insulation is better at lower moisture content. However, with increase in moisture content, the diffusion resistance increases, leading to decrease in permeability of the fabric. Dampness in the clothing affects its compressibility and eventually diminishes its thermal insulation[9]. The influence of relative humidity on comfort temperature was studied in a laboratory on a sample of 360 women and 360 men in the age group 18-23 years wearing standardised clothing for thermal insulation[9]. The results presented in Fig. 2 show gradual decrease in comfort temperature for both the genders with increase in relative humidity. It is also seen that the comfort temperature is slightly higher for women than for men, which may be due to variation in physiological responses to environmental temperature, because of differences between the two genders in average skin surface area and fat content of the body.

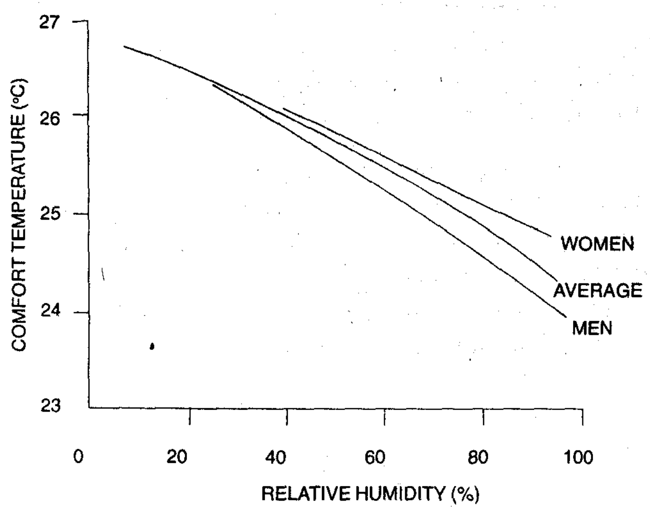


**Figure 2. Relative humidity *vs* comfort temperature**

Studies conducted at the US Army Research Institute of Environmental Medicine (USARIEM) have shown that when subjects were exposed to higher altitude in a chamber at the same temperature level as at sea, there was fall in skin temperature and they felt cold[10]. This is probably due to an increase in diffusion loss of insensible perspiration at high altitudes.

## 5. DEVELOPMENTS IN INSULATING MATERIALS

Microfibres of < 1 dtex available in the market are excellent insulating materials with reduced bulk because of their fine structure. Albany International's *Primaloft* is such an insulation material made from a blend of polyester microfibres[11]. Its performance is similar to that of duck or goose down. However, unlike down, *Primaloft* maintains its insulation properties in wet condition also. *Primaloft* clothing were used during the 1990 Mount Everest International Peace Climb. Tempofil of Neidhart & Co. is another insulating wadding made of microfibre with excellent thermal insulation[12].

A recent development in the area of insulating materials is the microencapsulated phase[13] change materials (micro-PCM). The technology for production of these novel materials involves the use of fluid capsules which are either applied as a coating over the fabric or directly incorporated into the fibre before extrusion of the dope. These fluid-filled capsules change their phase when they absorb heat and retain the heat nearly three times longer than the air entrapped in lofted insulation. These materials retain their insulation properties in damp conditions also. A micro-PCM developed by Gateway Technologies has insulation performance 400 per cent higher than those of conventional lofted insulation materials. Though its insulation properties are excellent, its exorbitant cost initially restricts its application to skiwear and fire safety applications.

Another theme of ongoing research on insulating materials is the development of shape memory polymer[14] coating based on polyurethane(PU). The polymer has elastic memory effect and it responds at molecular level. This enables the molecular structure of the polymer coating to open when the wearer gets hot, thus allowing the body heat and vapour to escape. When the atmosphere is cold, the molecular structure closes, preventing loss of metabolic heat to the environment thereby keeping the body warm. This polymer coating simulates the human skin and can be applied over polyester, cotton, nylon and silk. This coated fabric is termed as dream cloth and is being developed by Mitsubishi.

*Goretex*, a moisture permeable waterproof cloth, otherwise called breathable fabric, is used as the outermost layer in cold weather clothing. It is a microporous film of teflon (polytetrafluoroethylene) laminated between two layers of textile fabric to give a fabric which is impermeable to liquid water and forced air currents, but is highly permeable to diffusion of water vapour. According to some reports, micropores in the *Goretex* fabric get clogged up with dirt and sweat and prevent passage of water vapour out. To alleviate this problem, *Goretex* has produced a second generation laminate by applying an additional film to preclude soiling out. Adding a new dimension in this field, Unitika has developed the polyamino acid derivative (PAU) resin material *Exceltech*[15]. Though the process for the production of *Exceltech* is similar to that for moisture permeable waterproof polyurethane-based materials, the former shows superior smoothness and cold resistance than the latter. The slightly undulated surface of *Exceltech* gives a smooth feel. Cross-sectional view of *Exceltech* shows many thin, hollow structures and the surface is covered by many tiny pores of < 1dm diameter.

## 6. DESIGN CONSIDERATIONS

Thermal regulation of the human body depends on the maintenance of a balance between production, distribution and loss of heat. The mean skin and core temperatures of human body are 33 °C and 37 °C, respectively and stability of these core and skin temperatures is essential to avoid any cold or heat-related problems. Even a slight change in these temperatures leads to discomfort to the body and reduced efficiency. In cold environment, additional clothing must be worn to retard the loss of heat. The clothing should balance the heat loss against metabolic heat production to maintain the core temperature of human body at 37 °C. 70-80 per cent of this metabolic heat is lost through radiation and convection (non-evaporative), whereas the remaining 20-30 per cent is lost through respiration and insensible perspiration[16] (evaporative).

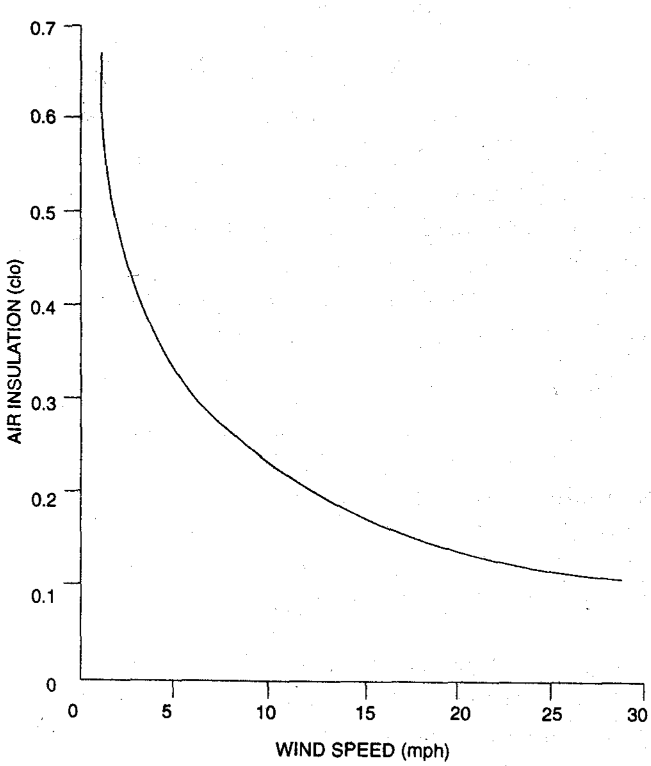


**Figure 3. Effect of wind speed on air insulation**

Non-evaporative heat loss can be controlled by insulating the clothing. Insulation of clothing should reduce heat loss and is directly related to the volume of air within the layer and between the layers. The air entrapped between the cloth and the skin also contributes a part of the insulation. The multilayer concept in cold weather clothing is to trap more air, which, in turn, gives better insulation. In addition, wind speed and wind chill factors associated with low temperatures also must be considered in the design of clothing. This is because the speed of wind disturbs the boundary air layer of the clothing, thus changing the insulation value of the clothing[17] (Fig.3).

### 6.1 System Design

A protective clothing system design necessitates multilayer clothing for higher efficacy and increased warmth. This theoretical consideration is verified by the fact that during winter, individuals load themselves with a number of clothing. People living in hills would always be wearing pullovers, coats, overcoats and covers for head and feet. However, a soldier has to be combat effective as well as well-protected against sub-zero temperature and high wind chill effects. He should not be loaded with a number of layers of different types of pullovers, coats, overcoats, etc., which may increase weight as well as bulk. So, system design becomes very critical and choice of different layers and their order of arrangement in a multilayered garment are matters of prime concern for the efficacy and effectiveness of the clothing for the soldier.

The designers try different combinations in the endeavour. However, discussion are restricted to the protective clothing developed by DMSRDE, which have been extensively undergone user trials and recommended for introduction in the Army.

Most of these clothing have arrangements of layers in the following order:

(a) *Outermost layer* : Water repellent, preferably breathable so that water does not enter the fabric and water vapour or sweat may escape out. In most of the protective clothing developed by DMSRDE, chemically–treated water and oil repellent fabric outers are popular. Alternatively, PU-coated nylon fabric or *Goretex* makes the outermost layer.

(b) *Middle layer*: Lightweight insulating filling type material like polyester batting or any new insulating material forms the middle layer. DMSRDE has developed clothing using polyester batting for lightweight and better loft, which allows increased entrapment of air.

(c) *Innermost layer*: Lightweight material like pile fabric, which may entrap more air for high insulation, forms the innermost layer. DMSRDE has developed clothing using acrylic pile fabric of different constructions and pile heights.

(d) *Reflective layer*: Sometimes the requirement is to create an added effect to reflect back metabolic heat to the body, so that it is not dissipated to the environment through the clothing. DMSRDE has developed clothing using aluminised nylon fabric for such effects.

These arrangements would be elaborated through DMSRDE-developed clothing systems, discussed hereunder:

Details of some of the DMSRDE-developed clothing systems are:

(a) *Jacket ECW has*: (i) outermost layer has made of 125 g/m$^2$ nylon fabric, chemically-treated for water and oil repellency, (ii) middle layer made of polyester batting, and (iii) innermost layer made of acrylic pile fabric. Thermal insulation value of the store is 81.6 per cent.

(b) *Waist Coat ECW has* (i) outermost layer made of 65 g/m$^2$ nylon fabric, chemically-treated for water and oil repellency, (ii) middle layer made of aluminised fabric, and (iii) innermost layer made of acrylic pile fabric. Thermal insulation value of the three-layered waistcoat is 80.3 per cent.

(c) *Trousers ECW has* (i) outermost layer made of 95 g/m$^2$ nylon fabric, chemically–treated for oil and water repellency, (ii) middle layer made of polyester batting, and (iii) innermost layer made of 65 g/m$^2$ nylon fabric. Thermal insulation values of the three-layered ensemble is 74.8 per cent.

(d) *Cap Glacier* has (i) outermost layer made of 250 g/m$^2$ nylon fabric with water and oil repellent treatment, (ii) second layer made of polyester batting, (iii) middle layer made of aluminised fabric. (iv) inner layer made of acrylic pile fabric, and (v) innermost layer made of Angola woollen shirting cloth. This five-layered assembly has thermal insulation value of 85.7 per cent.

(e) *Gloves* have two sides: (i) dorsal, and (ii) palm side.

Dorsal side has (i) outermost layer made of polyurethane-coated nylon or *Goretex* fabric, (ii) middle layer made of polyester batting, and the (iii) innermost layer made of acrylic pile fabric. The three-layered ensemble has thermal insulation value of 87 per cent.

Palm side has (i) outermost layer made of nappa leather for high abrasion resistance and inner layer made of acrylic pile fabric. The two-layered assembly has thermal insulation value of 78.9 per cent.

## 7. RESULTS & DISCUSSION

System design of protective clothing for extreme cold weather should be such as to repel water and snow, but to prevent heat from dissipating to the environment. The primary function of clothing insulation is to give comfort to the wearer by preventing body heat from escaping out more rapidly than it is produced. The lower the rate of heat flow, the greater is the heat resistance of the material. Moisture increases the rate of conduction, because water fills the fabric voids and conducts heat more rapidly than air. Clothing must permit the moisture vapour to flow out of the clothing to avoid condensation of sweat inside the clothing at low temperature. The efficiency of a soldier in the field under cold climate is affected to a considerable extent by the clothing worn. The clothing must be compatible during rigorous operations as well as during prolonged periods of inactivity. Many insulating materials are available in the market and one has to keep in mind all functional requirements of the protective clothing before selecting a suitable material for designing the clothing. Choice of materials and their different combinations is the most critical part of system design. DMSRDE has developed expertise over the years in the development of protective clothing for use in extreme cold regions. These clothing are generally based on multilayer principle. Laboratory evaluation puts these clothing as an excellent achievement in system design and field trials have established their superiority over the protective clothing currently in use.

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