MATERIALS AND CLOTHING DESIGN

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Introduction It is common to look at protective clothing solely in terms of the materials from which it is constructed. Materials are important, but design is equally important, as is the doctrine of how clothing should be used. A good example is clothing for the Arctic. Traditional Inuit clothing is superior to that taken into the North by modem Southern adventurers despite, not because of, being made of local materials. The design of the clothing, with its mode of use, is one that protects the wearer from a hazardous environment yet allows him to thermoregulate without sweating. It is a fundamental problem of protective clothing that almost any material interposed between the skin and the environment in order to protect interferes with thermoregulation. The problem can be reduced by materials improvements, but a full solution can only be achieved by designs, possibly designs including active elements. This paper considers several hazardous environments and attempts to analyze what can be achieved by materials and what must rely on designs.

Cold Protection against cold requires clothing which has insulation and windproofness. Insulation requires: a predominately gaseous layer to control conduction; some solid to eliminate free convection; and solid surfaces which control radiation. In existing materials 30 to 70% of heat transfer is by radiation which can be eliminated with improved he-fibre technology. Higher values of insulation/thickness or insulation/mass are foreseeable. Combining the theories of radiative and convective heat transport[1,2], predicts that a thermally optimum batting would have a fibre diameter of about 2 micrometres and a density of .07 kg/m^3 giving a ratio of insulation to mass per unit area of about 27 m^4 K/ kg W. Existing polyester battings have a ratio of up to about 4 and down about 6. Windproofness is relatively easily achieved with tightly woven or coated fabrics and effective closures. It is possible to provide total protection against cold anywhere on earth for even sedentary personnel using existing materials. About 10 to 15 cm of clothing thickness is required, achievable with 5 kg in mass. It should be possible to reduce these figures by one half, but the clothing would not necessarily be wearable because of an inability to evaporate sweat if the user increases his activity level.

Vapour diffusion resistance increases with fabric thickness, and condensation of sweat into clothing is almost inevitable in the cold. It can be demonstrated that heat loss through perfectly permeable insulation, even in the presence of condensation, is given by:

$$Q=(k/d)(T_s-T_a) + (DxH/d)(C_s-C_a)$$

where T_s,T_a,C_s,C_a are skin and ambient temperatures and water vapour concentrations, k is the dry thermal conductivity, D is the diffusion constant, H is the latent heat of vaporization and d is the material thickness. Hence, the ratio of wet to dry heat loss can be estimated to be 26 at 0 C and 1.8 at -40 C for a 50% RH environment This is inadequate to compensate for variations in metabolic heat production between rest and hard work The fraction of evaporated sweat which will condense is 84% at 0 C and 99% at -40 C. Also, a large fraction of sweat produced will not evaporate. Accumulated water eventually degrades the clothing insualtion.

It is possible to create designs which trap condensed water harmlessly in the clothing, but the quantity that can be handled is limited, and the full cooling potential of the sweat is still not achieved. Designs which permit the reduction of insulation with an increase in metabolic rate are necessary, and should be possible in most circumstances, eg. by appropriate layering? Auxiliary heating units for the cold are available but should not be necessary unless the user is injured. All the basic technology for complete cold protection exists. It needs to be developed into clothing which is convenient as well as protective.

Rain and Snow Complete waterproofness requires a continuous polymer membrane or coating. Ones that are also water vapour permeable and seam sealable are readily available . Even with ideal materials, the rate of evaporation of sweat is Iiited by air layers trapped under waterproof Clothing. Ventilated clothing has been tried many times, but never with total success. Potential exists for designs that permit: the convenient donning and doffing of rainwear, ventilation which is effective without compromising waterproofness, and the absorption and slow release of water vapour to prevent sweat soaking of inner clothing. The same materials have made dramatic improvements in foot and hand wear for cold wet weather. It is possible to exclude external water but allow the skin to dry after periods of sweating. This drying of the skin, socks and inner gloves worn inside a waterproof liner is possible even if the boot or outer glove is wet[4]. There is also potential for the use of wicking structures to move water up the leg or arm to a region where it may evaporate more quickly. Although these materials are widely accepted by users for their protective properties, they are still judged uncomfortable during periods of light sweating. One reason for this (though probably not the only one) is that they only achieve their highest vapour permeability when they are fully wet[5]. In nearly dry conditions, they have very low permeability. Improvements in the polymers could alleviate this problem.

Heat Protection against heat from fire or radiant sources mirrors protection against cold, except that radiation is more important with higher temperature heat sources and, of course, that normal materials bum. Aramid materials are resistant to very high temperatures and heat fluxes, so that fire resistance may almost be taken for granted and protection becomes a matter of insulating the skin. Pmtection is limited by the requirement to dissipate sweat and the tolerable weight or thickness of clothing. Lighter, thinner materials are possible and *can* help since sweat evaporation increases as thickness decreases. Ventilation can help in some environments where the hazard is mostly radiative, but will reduce protection where convection is significant. Ultimately the, solution is probably active cooling, but it is in principle possible to make materials which conduct heat better in one direction than the other or increase their insulation in response to high temperatures.

Chemicals Chemical protection may be achieved by liquid and vapour impermeable clothing or by permeable clothing with adsorbents such as charcoal. Coatings and membranes exist which are impermeable to some chemicals but permeable to water vapour. New polymers with wider ranges of protection should be possible, eg. by incorporating neutralizing chemicals to protect against a range of agents. For thermoregulation, the ideal design of a chemical garment is one that is very thin, is water vapour permeable and fits like a second skin. If a loose fitting garment is worn, especially over other clothing, heat and moisture flow are limited by trapped air, so that active ventilation or cooling is required in extreme heat A simple, but effective form of auxiliary cooling is a wettable outer shell which can raise heat loss in impermeable garments to the same level as in equivalent permeable garments.

Cold Water Immersion Thermal protection in water requires insulation which is totally waterproof. This maybe inherent as in closed cell foam, or achieved by inflation. The main difficulty is again in heat and moisture dissipation. Materials development offers some potential for improved sweat evaporation[6], but this will come at the expense of in-water insulation. Inflatable suits dissipate heat better, but are totally impermeable to sweat Vapour permeable inflatable structures have been created for other applications' and could find application here. There is considerable scope for innovative designs which enable insulation to be deployed only when required, rather than be worn constantly. There is also potential for the use of auxiliary heating in conjunction with minimal insulation. There is evidence' that good hypothermia protection *can* be achieved by insulating only the head and torso since vasoconstriction minimizes the influence of heat loss from the limbs on core temperature. Clear, quantified evidence of this effect could make simpler, more comfortable designs acceptable.

Design and Doctrine Since all protective clothing imposes limitations on the ability of the wearer to thermoregulate, he should be aware of those limitations are and the signs that they are being approached or exceeded. The first sign of cold stress is often cold toes as a result of vasoconstriction. The first sign of heat stress is the onset of sweating. A knowledgeable person can use these two signals to prompt the adjustment of clothing insulation or metabolic activity to restore thermal balance. Avoidance of thermal stress by the control of Clothing insulation is only possible if clothing is adjustable without loss of key protective elements. Layered clothing cannot be adjusted by the removal of layers if the essential protection is present only in the outermost layer and must be worn continuously. To avoid this problem, clothing should be layered so that an inner layer, or several layers, contain the essential protection. To make thermoregulation while wearing protective clothing possible, tasks, transportation, load carriage, workspaces etc., should be designed to allow forvariation in activity levels and the adjustment of clothing. This must be on an individual, rather than on a group, basis as metabolic rates vary among individuals. It is difficult to remove clothing on the job if there is nowhere to store or carry the extra garments, or if a brief interruption of the activity is not allowed.

Summary Comfort, thermoregulationand survival depend on; the environment, clothing and activity. Most problems are a result of incompatibilities among these. Usually, the environment is fixed, but both clothing and activity can be controlled by the user to some degree. Some problems will be alleviated by materials advances alone, but in general, clothing designs and doctrines need to be developed in harmony.

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