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HEAT LOSS THROUGH WET CLOTHING INSULATION

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DEFENCE RESEARCH ESTABLISHMENT OTTAWA

TECHNICAL NOTE 82-28

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ABSTRACT

Experiments and calculations were performed to identify the dominant mechanisms of heat flow through clothing insulation when wet, the initial water content of the insulation being 50 to 250% of the dry mass. It was found that all the heat flow could be explained as a combination of radiation, conduction by trapped air and diffusion of water vapour. The heat loss through wet insulation was found to be principally a function of thickness and of water uptake. Thus fibres which are water repellent give better wet insulation properties.

RÉSUMÉ

On a effectué des expériences et des calculs afin de découvrir les principaux mécanismes du flux de chaleur passant à travers le revêtement isolant d'un vêtement lorsqu'il est mouillé, la teneur en eau initiale du revêtement étant de 50 à 250 % de la masse sèche. On a découvert que l'on pouvait expliquer tout le flux de chaleur par une combinaison des facteurs suivants: radiation, conduction par l'air bloqué et diffusion de vapeur d'eau. On a constaté que la perte de chaleur occasionnée par l'humidité du revêtement isolant était fonction principalement de l'épaisseur des fibres et de la quantité d'eau. Par conséquent, les fibres hydrofuges constituent un meilleur isolant.

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INTRODUCTION

The choice among various insulants such as synthetic fibre battings or down and feather mixtures for use in cold weather clothing or sleeping bags is usually made on the basis of their thermal and mechanical properties when dry or conditioned at moderate relative humidities. However, there exists the possibility that the clothing insulation may become wet during use, for example, from rain or melting snow, from soaking up of unevaporated sweat or from accidental immersion. The thermal and mechanical properties of the insulant when wet may therefore be as important as when dry especially when the garment is intended for use in wet-cold conditions.

A study performed for the UK Ministry of Defence (1) compared the water uptake qualities of two polyester fibre battings and a down and feather mixture and found large differences. The polyester battings retained about twice as much water as the down and feathers. This study went on to compare the thermal resistances of the three insulants at various levels of water content. Here the differences were not quite as large. At 50% water content the polyester battings had 35% of their dry thermal resistance and the down and feathers, 23%. (The water content is the mass of absorbed water divided by the mass of the dry material.) On the basis of the water uptake the down and feather would seem more desirable but on the basis of thermal resistance measurements, the polyester seems better. This is not very helpful if a selection has to be made.

In this paper we report on experiments similar to those performed in the UK but more extensive in that we have tried to identify the heat flow mechanisms that are operative in the wet insulation so that the difference among different materials can be understood. We have been aided in this by the numerical models of heat and vapour flow described in a previous paper (2).

MECHANISMS OF HEAT TRANSPORT

In a previous paper (3) it was shown that in dry batting of about 1% fibre volume the majority of the heat is carried by two mechanisms, air conduction and radiation, with a small contribution from conduction by the fibres. To a good approximation these three can be described by a total thermal conductivity which is the sum of the three

$$k = (1-f)k_A + fk_F + k_R \qquad [1]$$

where k is the total conductivity
k_A is the conductivity of still air
k_F is the conductivity of the solid of the fibres
k_R is the radiative conductivity
and f is the fraction by volume of fibre.

For the wet batting, there are, in addition, the possibilities of heat conduction by liquid water, diffusion of water vapour and transport of liquid water by wicking.

For a wet batting, with ∿100% water content, conduction by liquid water may add to the overall conductivity a term of the order of

$$fk_W \simeq 0.01 \times 0.6 \frac{W}{m\ K} = 0.006 \frac{W}{m\ K}$$

This, when compared to the dry conductivity of about 0.045 W/m K, is quite small and is even smaller in relation to the overall heat transport in the wet material which exceeds the dry value by a factor of 3 or 4. Accordingly conduction by liquid water is negligible.

Heat transport by the diffusion of water vapour comes about primarily because there is a temperature gradient within the batting. Since there is liquid water present, the vapour pressure at any point within the batting is given by the saturation vapour pressure at the local temperature.

Thus

$$P(x) = P_s(T(x)) \qquad [2]$$

where P is the vapour pressure,
P_s is the saturation vapour pressure, a function of temperature,
T is temperature,
and x is the position within the batting, measured from the hot boundary.

Since T varies with position, so does P and heat is carried by the evaporation of water at a point close to the hot boundary, diffusion towards the cold boundary and either condensation at some cooler point or eventual escape into the environment. The flow of heat due to diffusion at any point is given by

$$Q_D = -H\, k_v \frac{dP}{dx} \qquad [3]$$

where H is the latent heat of vaporization of water and k_v is the "vapour conductivity" of the batting. k_v is essentially the diffusion constant of water into air, but expressed in mass and pressure units, since, as the batting is 99% air, the fibres do not greatly impede diffusion. The value of k_v is, at room temperature, 1.8×10^{-10} kg/s m Pa.

The total heat flow within the batting is the sum of the diffusive contribution and the sensible heat flow due to the overall conductivity

$$Q_T = Q_D + Q_S \qquad [4]$$

where

$$Q_S = -k \frac{dT}{dx} \qquad [5]$$

Since water evaporates and condenses at various points within the insulation, the diffusive and sensible heat flows are not independent and vary with time as the insulation dries. The numerical models described in reference 2 predict this combined heat and vapour flow through any set of clothing materials for which the thermal and vapour conductivities are known. For a thick layer of insulation, the thermal conductivity is readily measured and, as noted above, the vapour conductivity is essentially that of still air.

There are two effects that may be important in the wet insulation that are not taken into account in the numerical models. These are the change in thickness of the material with water content and the wicking of water. An initial set of experiments was therefore performed in an unrealistic but theoretically understandable manner with the thickness of the insulation fixed. From the agreement between the experiment and the theoretical predictions it can be concluded that wicking is of little significance.

The apparatus for this first set of experiments is shown in Figure 1. In order to maintain a constant thickness the sample insulation was held between two layers of an open weave polyester mesh fabric attached

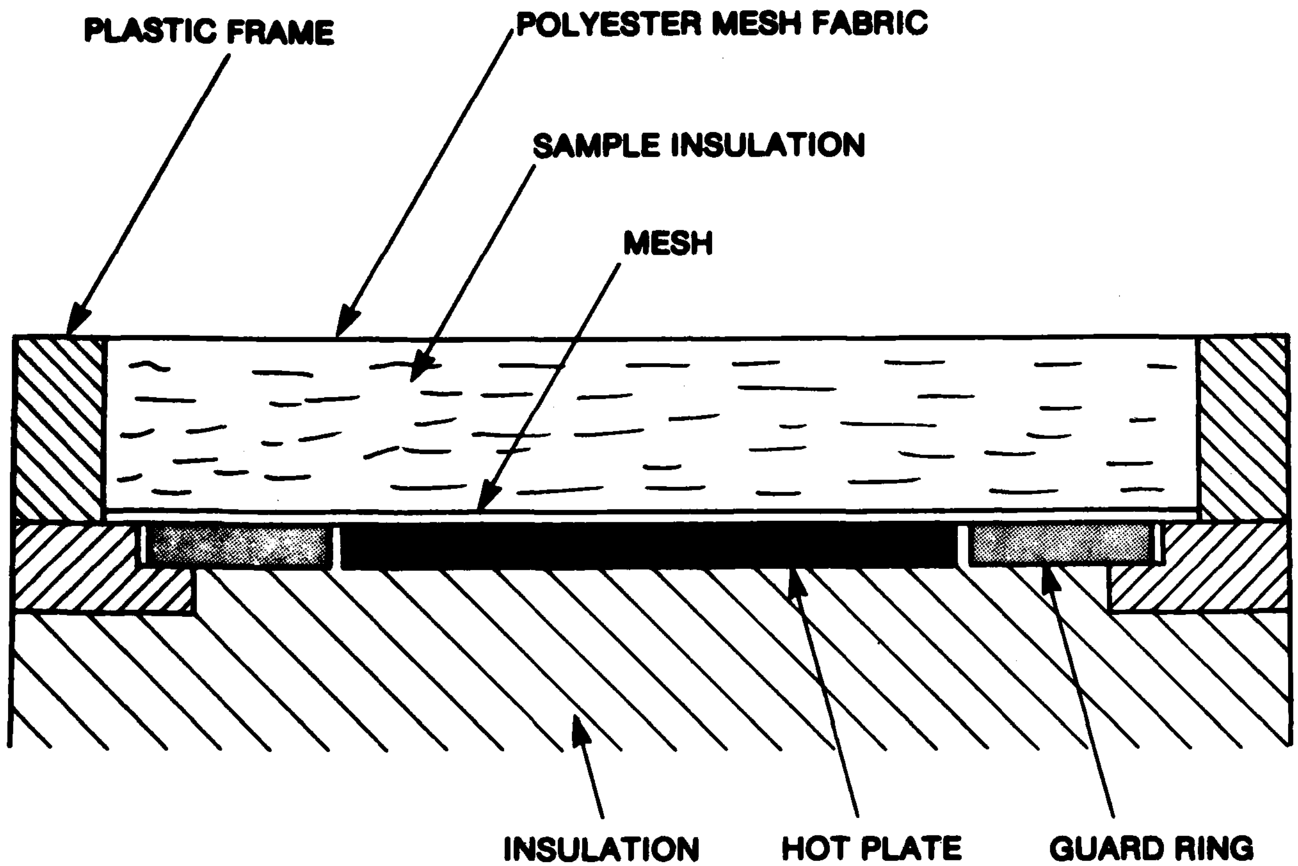

Figure 1: Apparatus for measurements with a fixed thickness of insulation. The sample is held between 2 sheets of a polyester mesh fabric in a rigid plastic frame. The heat loss from the hot plate is monitored as the sample dries.

to a rigid plastic frame. The sample was wetted and placed on the hot plate to dry with the heat loss from the plate, maintained at a constant temperature of 35°C, being monitored continuously. The details of the hot plate have been described in a previous technical note (4). The sample thickness was 13 mm in all cases and the atmospheric conditions were about 22°C and 30% RH although these were not carefully controlled.

The samples were wetted by immersing in distilled water, draining, and shaking by hand to remove excess water. Many trials were performed with different immersion and drain times and techniques of shaking in order to establish a reproducible procedure. The mass of water retained in the sample and mesh varied greatly with the different procedures but each individual procedure gave results reproducible to a few percent and the order of the various samples in the degree to which they took up water was the same in all trials. The technique finally adopted as standard was as follows.

A 6 mm diameter hole was drilled through the side of the plastic frame to permit water to flow easily into the sample. The frame was immersed in distilled water to an average depth of 20 cm with the axis of the cylindrical sample held horizontally. For about 5 minutes the frame was slowly rotated (15 s per rotation) about this axis to disperse water throughout the sample. The frame was then held out of the water with the hole downward for 1 min while the bulk of the water drained out. It was then shaken by hand, by being dropped through a height of about 50 cm and stopped abruptly, until no more water could be shaken out or to a maximum of 40 shakes. Any water on the frame itself, rather than in the sample or mesh fabric, was wiped off and the frame was weighed. The frame was then either placed on the hot plate to dry or was dismantled and each component weighed individually to determine the distribution of water among the two layers of mesh and the sample itself.

The samples were the continuous filament polyester batting (PolarGuard), 100% goose down, a polypropylene staple fibre batting and PolarGuard with a Zepel-B water repellent finish (about 1% add-on). Areal densities were in the range 0.2 to 0.25 kg/m^2. The polyester mesh as 0.033 kg/m^2 in density, about 0.3 mm thick with about 0.4 mm pore size. For some experiments the mesh was also treated with Zepel-B. The masses of water taken up by the various samples are shown in Table I.

As may be seen from Table I, the PolarGuard and polypropylene samples retained the largest quantity of water, the down less, and the water-repellent treated PolarGuard the least. A small but significant quantity of water was taken up by the mesh fabric when not treated but a negligible quantity was soaked up by the Zepel-B treated mesh.

These masses of water were used to specify the initial conditions for the calculations. The complete system was represented numerically by 13 layers: the bottom layer of mesh, the sample divided into 10 layers, the top layer of mesh and an adhering still air layer of 10 mm thickness. The thermal resistances of the dry samples were all about 0.32 m^{2}K/W.

Figure 2 shows a comparison of the theoretical prediction and the experimental results for PolarGuard and the mesh both untreated. For the

TABLE I

Dry Masses and Masses of Water Taken Up for Experiments at Fixed Sample Thickness

Sample				Mesh			
	Dry Mass kg/m²	Mass of Water kg/m²	% Water Uptake		Dry Mass kg/m²	Mass of Water kg/m²	% Water Uptake
		(±.01)	(±5)			(±.005)	(±15)
Polarguard Untreated	0.23	0.57	250	Untreated	0.033	0.04	130
"	"	0.62	270	Treated	"	0.01	33
Down	0.21	0.30	140	Untreated	"	0.10	330
	"	0.23	110	Treated	"	0.01	33
Polypropylene	0.25	0.60	240	Untreated	"	0.04	130
PolarGuard Treated	0.23	0.24	105	Untreated	"	0.05	170
"	0.23	0.23	100	Treated	"	0.01	33

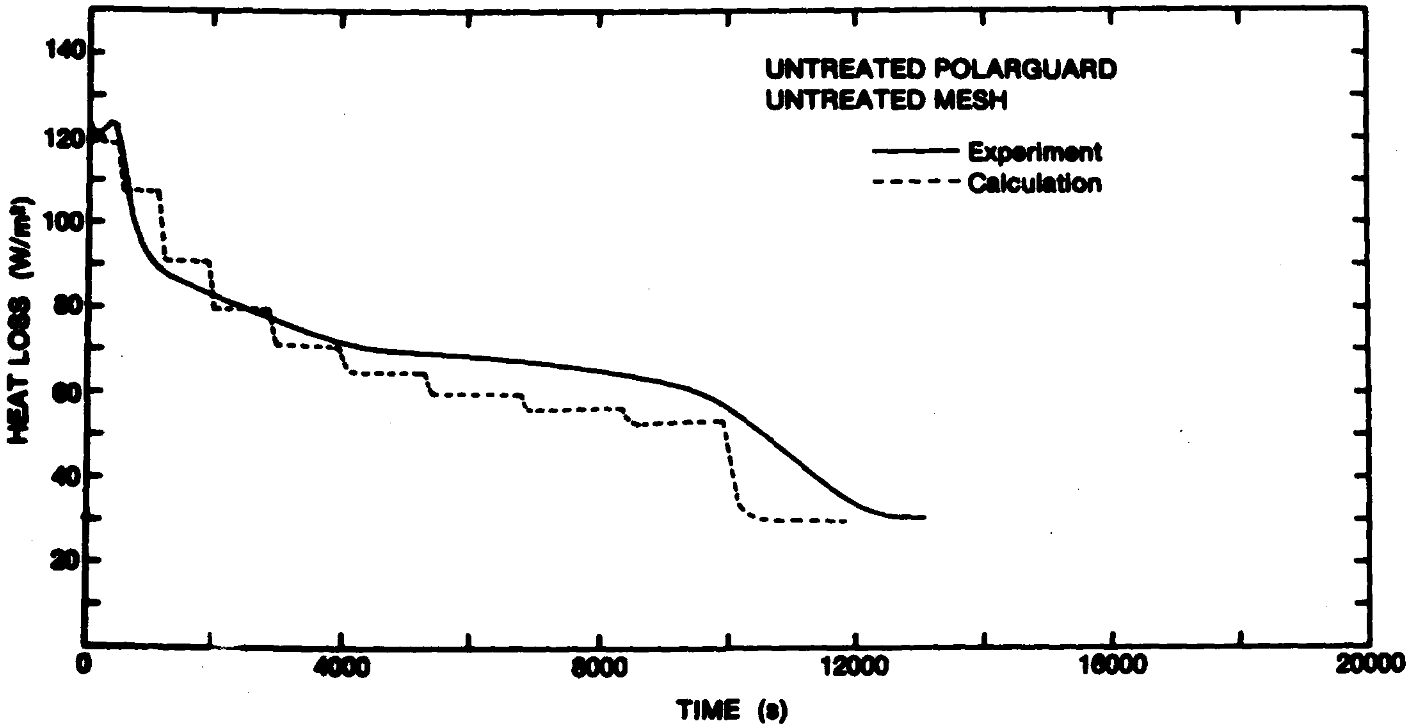

Figure 2: Heat loss during drying for a sample of PolarGuard, not water repellent treated, at a fixed sample thickness of 13 mm between layers of polyester mesh, also not treated.

most part the stepped nature of the theoretical curve is due to the representation in the theory of the PolarGuard as a series of discrete layers rather than as a continuum but the first step is also visible in the experimental data and is physically significant. The first plateau at the level of 125 W/m^2, between times 0 and 1000 s, corresponds to the drying of the mesh fabric closest to the hot plate. This is, of course, a real physical layer and the plateau is in both curves. After all the water has evaporated from this layer, water evaporates from the region of the PolarGuard closest to the plate and a region of dry material expands outwards with time. The theory predicts this as a series of steps but the observation is of a continuum. At the same time as the inner portion of the PolarGuard is drying, the outer portion dries so that there is a wet region within the batting that shrinks with time from both edges simultaneously. The heat loss is most sensitive to drying that occurs close to the plate so it is high at first, drops rapidly as the closest regions dry, decreases more slowly as regions deep within the batting dry, and finally drops to its dry value as the last of the water evaporates.

By and large the agreement between theory and experiment is good if the discontinuous nature of the calculated curve is ignored. The initial heat loss with the sample totally wet is predicted to an accuracy of a few percent and the prediction of the total drying time (10,000 to 12,000 s) is in fair agreement with the experiment. The calculation does appear to underestimate the heat loss for much of the drying period and the origin of this discrepancy is unclear. One possible explanation is that there is some movement of liquid water downward, towards the plate, so that water is evaporating from points closer to the plate than predicted by the theory. However, the motion of water under gravity or by wicking cannot be greatly important or the drying time would not be predicted accurately.

Clearly the agreement between theory and experiment is close enough in these data to conclude that the basic assumptions of the theory, that the extra heat loss in the wet fabric is due to diffusion of water vapour and that wicking can be ignored, is largely correct.

Figure 3 shows the results of a similar experiment with PolarGuard but with water-repellent-treated mesh fabric. The main difference between these and the results with the untreated mesh is that the plateau between 0 and 1000 s is absent since the mesh contains very little water. The initial heat loss level is 90 W/m^2 rather than 120 in the untreated case. Again the predictions of the theory of the level of heat loss initially and the time to the final drop to the dry value are roughly correct although here the prolonged tail in the experimental data about 10,000 s is more apparently in disagreement with the theory. It is difficult to conceive of any reason why this should be so since by this time the mesh layers should be dry and their water repellent qualities irrelevant. Perhaps the initial distribution of water was not uniform, as is assumed by the theory, and was different in the two cases. Since the quantity of heat involved in this tail is only about 12% of the heat required to dry the sample, the point is minor.

In Figure 4 data for the case of both the PolarGuard and the mesh water repellent treated are shown. The heat loss again starts at the lower value of 90 W/m^2 and the sample dries in about 7,000 s (2 h) rather than

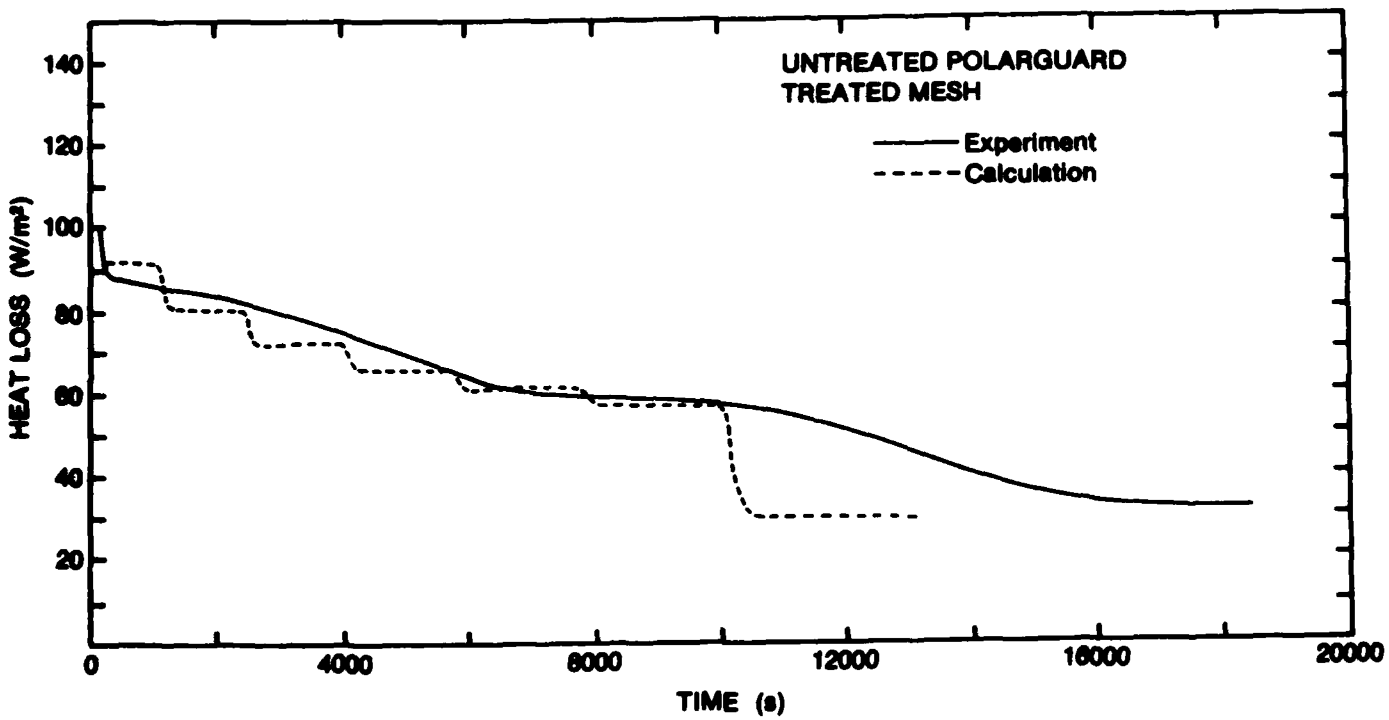

Figure 3: Heat loss during drying for untreated PolarGuard between layers of water repellent treated mesh.

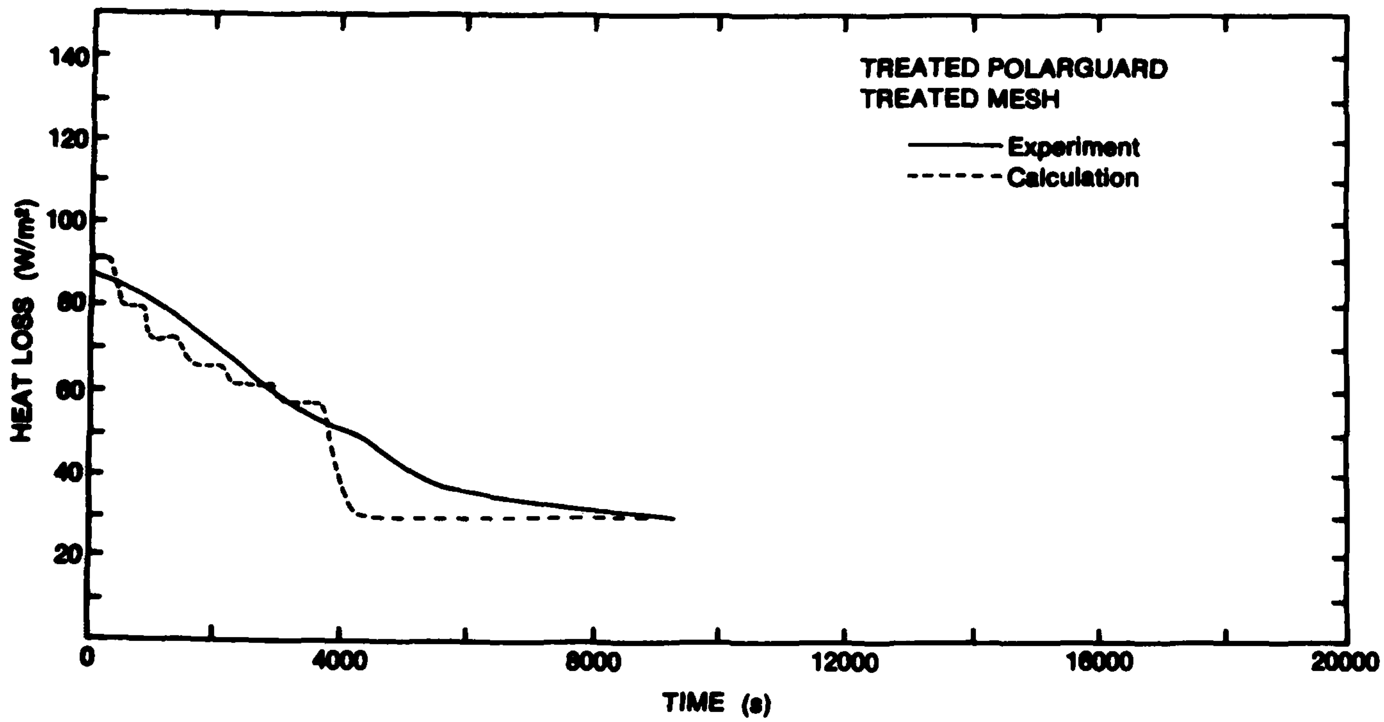

Figure 4: Heat loss during drying for water repellent treated PolarGuard between layers of treated mesh.

18,000 s (5 h) for the untreated PolarGuard. This is simply a consequence of the reduced water uptake in the treated sample.

Similar experiments were performed with a polypropylene sample (untreated) giving substantially the same results as with the polyester PolarGuard as may be expected since the water uptake was similar.

Experiments were also performed with samples of down with both treated and untreated meshes. The results are shown in Figure 5. The prediction of the calculation for the case of a treated mesh again is in good agreement with the experiment but there is substantial disagreement in the case of an untreated mesh. The theory in the untreated case predicts a rather long initial plateau due to the fact that the mesh picked up more water than with the other samples (see Table I). Experimentally this plateau is observed to be considerably longer than predicted. It should be noted that the down itself picked up more water with an untreated mesh than a treated one, 0.30 as opposed to 0.23 kg/m^2. A probable explanation for the observed discrepancy, therefore, is that the combination of the untreated mesh and the intrinsically water repellent down tends to concentrate water at the interface between the two giving rise to more water present in both the mesh and the down close to the mesh. The distribution of water in the down is not, therefore, uniform as is assumed in the theory, but higher close to the plate giving a longer plateau. Why this concentration should occur is not readily explained.

In all these experiments, the predictions of the theory seem to be sufficiently accurate that it may be concluded that the theory includes all the essential elements of the heat flow. Thus, the heat flow is predominantly by air conduction, radiation and diffusion and the effects of liquid motion can generally be ignored.

DRYING OF REALISTIC SAMPLES

Although the experiments on samples at a fixed thickness with boundary fabrics made of open weave mesh were useful in identifying the heat flow mechanisms involved, they do not yield all the information necessary to make a choice among insulating materials. The absorption of water may have an effect on the mechanical properties of the insulation which in turn will affect its thickness and thus its insulating value. Experiments were therefore performed in a more realistic manner on samples of insulation sewn between two layers of shell fabrics in a way that simulates their use in garments or sleeping bags.

The samples were sewn into discs with diameters equal to that of the hot plate (16 cm) and their thicknesses measured, dry, at minimal compression (0.16 kPa). A sample was wetted by immersion in distilled water

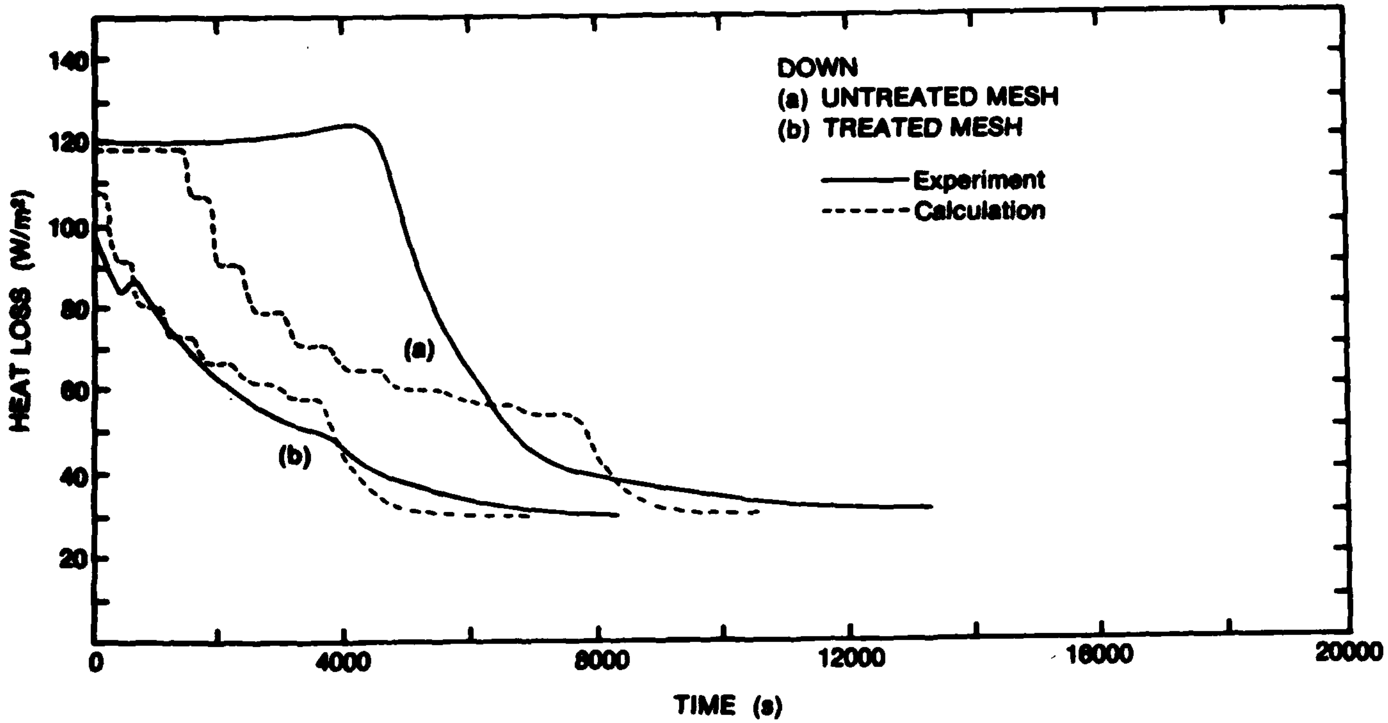

Figure 5: Heat loss during drying for down between two layers of (a) untreated, and (b) treated mesh.

for 60 s during which time it was squeezed by hand 10 times. It was then run between 5 cm dia. rollers under a force of 100 N (25 lbs) repeatedly and weighed after each 5 passes until the weight indicated that no more water was being squeezed out (typically 20 passes). The sample was then placed on the hot plate to dry. Thicknesses when wet were also recorded.

Insulation samples were again down, polypropylene, PolarGuard and Zepel-B treated PolarGuard. The shell fabrics used were a 0.069 kg/m^2 rip-stop nylon and 0.16 kg/m^2 nylon-cotton twill, Zepel-B treated. The wet and dry weights and thicknesses are shown in Table II.

Ideally in such a comparison of materials it is desirable to have all samples at the same mass and thickness. Unfortunately, this is not possible since the mechanical properties of the various insulants are quite different. The main comparison of current interest is between down, the insulation most generally viewed as the best for sleeping bags, and PolarGuard, one of the more likely alternates. Samples of these two were then arranged to have the same thickness and therefore about the same dry thermal resistance. The purpose of including polypropylene in this study was to ensure that the observed properties of PolarGuard were not peculiar to that particular brand of synthetic batting but more generally representative. A sample of the available polypropylene with the same thickness as the polyester would have had a very much higher mass and a very much higher water uptake so a sample of the same mass was chosen. It is not intended that any conclusions concerning the relative merits of polyester and polypropylene battings should be drawn from these experiments.

As may be seen from Table II, the quantity of water taken up by the samples, was, as in the case of the data with the frame, high for polypropylene and the untreated PolarGuard and very much lower for the treated PolarGuard and the down. It may also be noted from Table II that the changes in thickness of all the synthetics were small, 10 to 30%, but very large for the down, 80%.

The heat losses during drying for these samples are shown in Figure 6. The initial very high heat loss, when the samples were placed on the plate at time 0 s, was due to the heating of the wet sample from room temperature to close to 35°C. Each of the curves then drops to a plateau, the height and duration of which depend on both the sample thickness and the quantity of absorbed water, until the sample is nearly dry and then drops gradually to the dry heat loss value.

The curves for untreated PolarGuard and the polypropylene are very similar. The heat loss through the polypropylene was higher because the sample was thinner. The drying time in each case is about 5 h. The drying time for the down is much shorter, about 1 h, but at a substantially higher heat loss rate. The higher rate is due to the reduced thickness of the sample which causes a decrease in both thermal and vapour resistances. The shorter drying time is due to a combination of the reduced thickness, which increases the drying rate, and the lower mass of water that needs to be evaporated. The drying time for treated PolarGuard is again short since the amount of absorbed water is low and at a low level since the thickness of the sample is maintained even when wet.

TABLE II

Wet and Dry Properties of Samples Sewn in 160 mm Diameter Discs Between 2 Layers of Rip-stop Nylon Shell Fabric

Sample	Dry Thickness (mm)	Wet Thickness (mm)	Dry Mass (kg/m^2)	Mass of Water (kg/m^2)	Excess Heat Loss During Drying		
					MJ/m^2	Wh/m^2	MJ/kg
Polypropylene	9.0	8.2	0.42	0.87	1.2	340	1.4
Untreated PolarGuard	15.5	9.7	0.40	0.67	0.76	210	1.1
Down	13	2.5	0.34	0.26	0.46	130	1.8
Treated PolarGuard	14	11	0.43	0.22	0.14	39	0.6
Shell Fabric	-	-	0.14	0.03	-	-	-

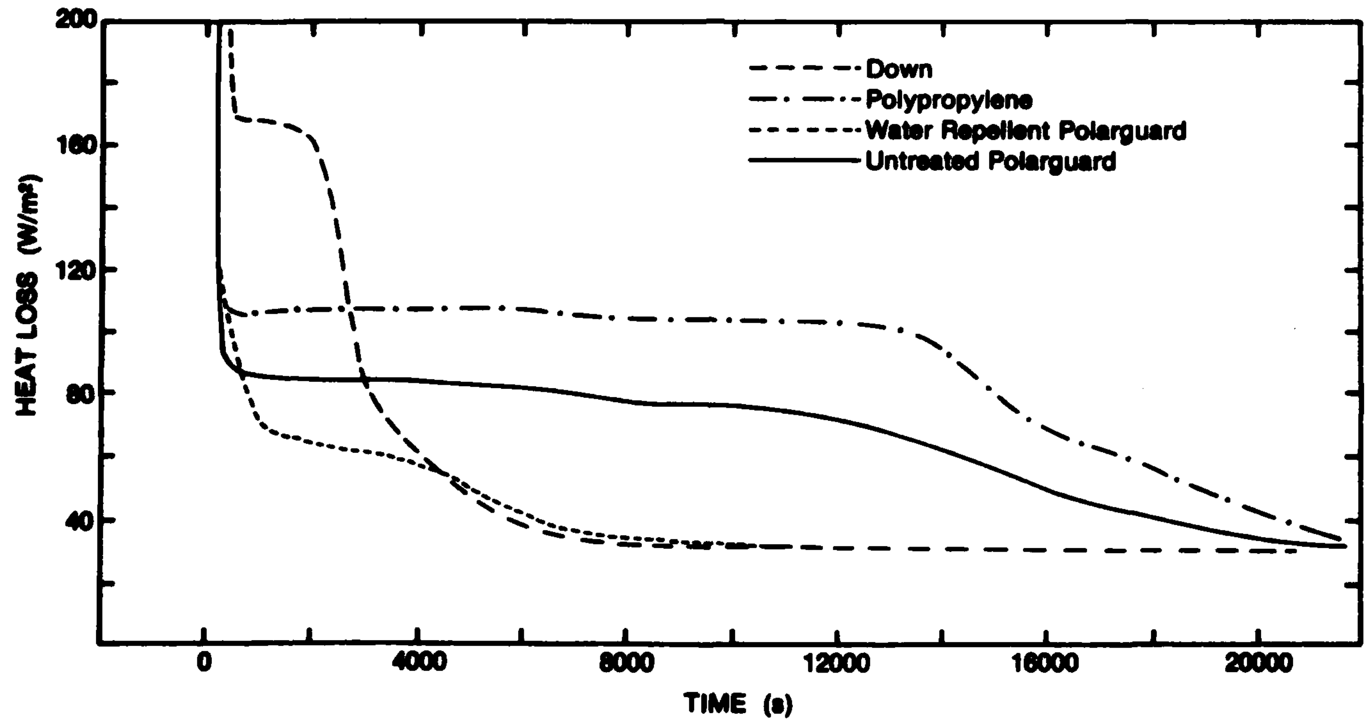

Figure 6: Heat loss during drying for various insulants sewn between layers of rip-stop nylon. The sample thickness is different in each case. See Table II.

A possible figure of merit for the characterization of the various insulants is the quantity of heat in excess of the dry heat loss that is lost over the drying period. This quantity is shown in Table II and may be seen to be, very roughly, proportional to the quantity of water absorbed. However, the heat loss during drying also depends on the thickness of the insulation, being relatively higher for the thinner samples. This is because not all the heat required for evaporation of the water comes directly from the plate. Some may be considered to come from the atmosphere. The closer the site of evaporation to the plate, the more the heat originates at the plate, and, as can be seen from Table II, the higher the heat loss per unit mass of water. The limiting value of this quantity is the latent heat of vaporization of water, 2.4 MJ/kg.

WETTING OF BULK SAMPLES

Since the experiments described above were somewhat idealized in order to ensure reproducibility, it was not certain that the quantities of water left in the samples after passing through rollers were comparable to those that might be left in a real garment or sleeping bag if wetted and wrung out in the field. Accordingly larger samples (60 × 60 cm) were constructed of PolarGuard and two shell fabrics, the 0.069 kg/m^2 rip-stop nylon and a 0.16 kg/m^2 nylon-cotton twill. The large samples were wetted and then wrung out by hand as well as possible. The mass and water uptake of these samples are compared in Table III to the results for the smaller samples squeezed between rollers.

As may be seen in Table III, the quantity of water left in the larger, hand wrung, samples was about twice that left in the smaller, machine-wrung samples and there was some variation with the type of shell fabric. Since many times the quantity of water left in the sample after wringing was initially soaked into the sample, the different water uptakes must be a result of the ease with which the water can be forced out of the sample rather than the degree to which it soaked in. Clearly the water retention properties of the shell fabrics themselves were not involved since the sample between one layer of rip-stop nylon and one layer of nylon-cotton twill retained only as much as that between 2 layers of rip-stop nylon. It is not clear what property of the shell fabric provides the limit.

The fact that the water uptakes in the bulk samples were a factor of 2 larger than those of the small samples should not affect the conclusions of the previous sections. It is not likely that the higher water content would introduce qualitative differences in the heat flow mechanisms but would simply increase drying times by about a factor of 2. Heat losses and drying times are, in any case, strong functions of atmospheric temperature and humidity and those presented here are in no sense typical.

TABLE III

Water Uptake of Bulk (60 × 60 cm) Samples

Shell Fabric	Dry Mass kg/m^2	Water Uptake kg/m^2
(a) 16 cm samples		
Rip-Stop Nylon	0.40	0.67
Nylon-Cotton Twill	0.67	0.90
(b) 60 cm samples		
Rip-Stop Nylon	0.40	1.3
Nylon-Cotton Twill	0.67	1.9
Combination*	0.53	1.3
None**	0.29	0.93

* A combination of both fabrics, one on each side of the sample.

** A 60 ×60 cm sheet of PolarGuard with no shell fabric.

CONCLUSIONS

The agreement between theory and experiment, though not perfect, indicates that the main mechanisms of heat flow in wet insulating materials are the two that are predominant in the dry material, namely air conduction and radiation, with the addition of diffusion of water vapour. Heat conduction by liquid water or the bulk movement of liquid water by wicking do not seem to be significant.

The heat loss during drying of a wet garment and the time to dry are determined by the quantity of water absorbed and the thickness of the insulation. A water-repellent treated polyester batting was the best of the materials under the conditions of the experiments. Since the agreement between theory and experiment is generally good it is possible to use the theory to predict the behaviour of any combination of insulation and shell fabrics, under any set of environmental conditions, from measurements of wet thickness and water uptake and of thermal and water vapour resistance when dry. The experiments presented here were not an attempt to duplicate exactly realistic conditions of use and the data should not be taken as representative of field performance. On the basis of these experiments, however, one may well conclude that the most desirable feature of an insulant that is to be wetted is that it retains little water when wrung out. The thickness of the insulation when wet and its apparent thermal resistance when wet are of secondary importance.

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13. ABSTRACT

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