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CALCULATIONS OF HEAT AND VAPOUR TRANSPORT IN CLOTHING:
TRANSIENT EFFECTS IN HYGROSCOPIC MATERIALS

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## ABSTRACT

A numerical model of heat and water-vapour transport through multi-layered clothing systems under transient conditions is presented. Taken into account are the condensation and evaporation of liquid water within the clothing layers and changes in the amount of water absorbed by hygroscopic fibres although the hygroscopic properties are taken to be of a very simple form. The calculations are compared to experiments reported by Woodcock in 1962, giving good agreement, and used to discuss the so-called buffering effect of hygroscopic clothing materials.

## RÉSUMÉ

Voici un exemple de réseau de circulation de la chaleur et de la vapeur d'eau applicable aux vêtements à couches multiples, de l'eau qui se trouve dans les couches de vêtement, de même que la variation de la quantité d'eau absorbée par les fibres hygroscopiques, sont prises en considération, même si les propriétés hygroscopiques sont considérées très élémentaires. Les calculs ont été comparés à ceux des expériences de Woodcock (1962), avec lesquels ils sont en bon accord, et servent à étudier l'effet dit "de tampon" des tissus hygroscopiques.

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# INTRODUCTION

Most of the research into heat and water-vapour transport in clothing has been concerned with steady-state conditions where a clothing system can be characterized by an overall thermal resistance and an overall vapour resistance. However, textile materials differ not only in their resistances but also in the degree to which their fibres absorb water. This absorption of water has no effect on the steady-state heat transfer unless the accumulation of water is sufficient to change the thermal or vapour resistances, but can have large effects on the transient heat transfer under varying conditions. These transients may be of many minutes or even several hours duration and so are important to overall clothing performance.

This paper describes a numerical model of the combined heat and water-vapour flow through multi-layered clothing systems under transient conditions taking into account the absorption or desorption of water by the *fibres and the condensation or evaporation* of liquid water but ignoring wicking of liquid water. The model assumes that each clothing layer can be characterized by steady-state thermal and vapour resistances that are not influenced by the presence of absorbed or liquid water. The moisture regain of the fibres as a function of temperature and vapour pressure is included in a simplified form, the regain being taken as proportional to the relative humidity.

The model is used to explain some transient effects observed experimentally by Woodcock in 1962 (1) and to investigate the so-called buffering effect of hygroscopic clothing.

# THEORY

## GENERAL FORMULATION

Consider a clothing system of several layers as illustrated in Figure 1. Let the geometry be planar so that the heat and vapour flows are one-dimensional and let heat and mass flow be by conduction and diffusion

only.  (Radiative heat transfer can be included with conduction but convection is excluded as is wicking of liquid water).  The heat flow at any point x and time t can be described by the differential equation

$$\frac{\partial}{\partial x}\left\{k_H(x)\frac{\partial T}{\partial x}(x,t)\right\} + Q_c(x,t) = C_H(x)\frac{\partial T}{\partial t}(x,t) \qquad [1]$$

Here   $T$ is the temperature,
  $k_H$ is the thermal conductivity,
  $C_H$ is the heat capacity per unit volume,
and   $Q_c$ is the quantity of heat per unit volume per unit time that is being liberated by the condensation of water vapour.

The flow of water vapour is described similarly

$$\frac{\partial}{\partial x}\left\{k_V(x)\frac{\partial P}{\partial x}(x,t)\right\} = \frac{\partial \rho}{\partial t}(x,t) \qquad [2]$$

where   $P$ is the vapour pressure,
  $k_V$ is the vapour conductivity analogous to the thermal conductivity,
and   $\rho$ is the total concentration of water.

The solution of equations [1] and [2] requires a further relation among the vapour pressure $P$, the density of water $\rho$, and the temperature $T$.

The total density of water is made up of contributions from water vapour, water absorbed by the hygroscopic fibres, and liquid water condensed on the fibres.  (No distinction is drawn here among the various ways in which water may be absorbed into the structure of the fibres or adsorbed onto their surfaces).  Thus,

$$\rho = \rho_V + \rho_A + \rho_L \qquad [3]$$

In the absence of the other two forms, the density of water vapour is related to the pressure by the ideal gas law

$$P = nk_B T \qquad [4]$$

where   $n$ is the number of molecules per unit volume,
and   $k_B$ is the Boltzmann constant.

If the mass of one molecule is $m$

$$\rho_V = nm = \frac{m}{k_B T} P \qquad [5]$$

or

$$\rho_V = C_V P \qquad\qquad [6]$$

where $C_V$ is the "vapour capacity" analogous to the heat capacity $C_H$ and is given by

$$C_V = \frac{m}{k_B T} \qquad\qquad [7]$$

In the presence of a hygroscopic material it is assumed that the water vapour is at all times in equilibrium with the water absorbed by the fibres. This assumption is valid as long as the equilibration times of the dominant absorption processes are much shorter than the times over which the heat flows are changing. Equilibration times have been shown to be a few seconds for wool (2) and the times for heat flow changes are hundreds of seconds. In general the quantity of water absorbed by a fibre at equilibrium (the regain) is a complex function of temperature and pressure

$$\rho_A = \rho_A(T,P) \qquad\qquad [8]$$

In this paper it is assumed that the regain is proportional to relative humidity alone and does not otherwise depend on temperature or on the history of the fibres. Thus

$$\frac{\rho_A}{\rho_F} = \gamma \, \frac{P}{P_s(T)} \qquad\qquad [9]$$

where     $\gamma$ is a material-dependent parameter,
          $\rho_F$ is the density of the fabric,
and     $P_s(T)$ is the saturation vapour pressure over water at temperature T.

This assumption is not essential to the theory but it does greatly simplify the computations at some expense in accuracy.

In the absence of liquid water

$$\rho = \rho_V + \rho_A$$

or

$$\rho = \left\{ C_V + \gamma \rho_F / P_s(T) \right\} P \qquad\qquad [10]$$

In the presence of liquid water it is similarly assumed that P takes its equilibrium value so that P may never exceed $P_s(T)$. Therefore the desired relation among P, $\rho$ and T is

$$P(\rho, T) = \min \left\{ P_s(T), \frac{\rho}{C_V + \gamma \rho_F / P_s(T)} \right\} \qquad\qquad [11]$$

## BOUNDARY AND INITIAL CONDITIONS

The boundary conditions on T and P (or $\rho$) may be specified in a variety of ways. The most appropriate, or at least the simplest, for physiological or hot-plate experiments seems to be to specify a temperature and humidity of the ambient air, a skin temperature and either a skin vapour pressure or a sweat production rate. Thus at the outer boundary (x=D) of the clothing we have

$$T(D,t) = T_A(t) \qquad\qquad [12]$$

$$P(D,t) = P_A(t) \qquad\qquad [13]$$

and at the skin (x=0)

$$T(0,t) = T_{sk}(t) \qquad\qquad [14]$$

and either, specifying a skin vapour pressure,

$$P(0,t) = P_{sk}(t) \qquad\qquad [15]$$

or, specifying a sweat rate

$$- k_V(0) \frac{\partial P}{\partial x}(0,t) + \frac{d}{dt} M_{sk}(t) = M_o(t) \qquad\qquad [16]$$

where $M_O$ is the sweat rate and $M_{sk}$ is the mass of water that has accumulated at the skin.

Under transient conditions some or all of the boundary conditions may vary with time.

In most of the calculations reported here the initial conditions are assumed to be those of the clothing systems conditioned to the steady-state temperature distribution in the absence of sweating and to ambient humidity.


## FINITE-DIFFERENCE EQUATIONS


The equations of the preceding section give the heat and vapour flows in a continuum but numerically these need to be solved at a set of discrete points. The finite-difference equations used in the solution can most easily be understood in terms of an equivalent electrical circuit as illustrated in Figure 2.

Each layer of clothing is represented by a resistance, r, and capacitance, C, equivalent to its thermal or vapour resistance and its thermal or vapour capacity respectively. (A thick layer may be split into several sub-layers and represented by several points). For convenience the air layers between the skin and the first clothing layer and between the last clothing layer and the ambient air are included explicity. Any other air layer, between clothing layers, may be included by treating it as a clothing layer like any other or by adding its resistance and capacitance to those of the clothing layers on either side.

The voltages, V, correspond to either temperatures or vapour pressures, the charges on the capacitors to accumulated heat or water and the current sources, I, to heat liberated by condensation of water vapour.

For boundary conditions of temperature and vapour pressure fixed at both the skin and at the ambient air, $V_{sk}$ and $V_A$ correspond to the skin and ambient temperatures and humidities. For boundary conditions on the sweat rate, the current source $I_{sk}$ corresponds to that sweat rate and $V_{sk}$ is free to vary. The capacitance $C_O$ right at the surface of the skin is only of relevance to vapour and only if a sweat rate is assumed.

To keep the algebra more compact and in correspendence to the usage in the computer codes let

$$R_0 = r_0 + \frac{1}{2} r_1$$

$$R_1 = \frac{1}{2} r_1 + \frac{1}{2} r_2 \qquad [17]$$

$$\vdots \qquad \vdots$$

$$R_N = \frac{1}{2} r_N + r_{N+1}$$

and denote vapour or heat resistance and capacitances by the subscripts V or H.

## Equations for Heat Flow

The equations for the temperature can be written down quite easily. If we have correspondences

$$V_{SK} = T_{SK}$$

$$V_i = T_i \text{ for } i = 1 \text{ to } N \qquad [18]$$

$$V_A = T_A$$

the change on each capacitor is

$$C_i V_i = C_{Hi} T_i \qquad [19]$$

and the currents $I_i$ correspond to heat liberation rates $Q_{Ci}$, then at the first clothing layer

$$\frac{T_{SK} - T_1}{R_{H0}} + Q_{C1} - \frac{T_1 - T_2}{R_{H1}} = C_{H1} \frac{d}{dt} T_1 \qquad [20]$$

at the second layer

$$\frac{T_1 - T_2}{R_{H1}} + Q_{C2} - \frac{T_1 - T_2}{R_{H2}} = C_{H2} \frac{d}{dt} T_2 \qquad [21]$$

Similar equations hold up to layer N-1. At the last layer

$$\frac{T_{N-1} - T_N}{R_{H,N-1}} + Q_{CN} - \frac{T_N - T_A}{R_{HN}} = C_{HN} \frac{d}{dt} T_N \qquad [22]$$

## Equations for Vapour Flow with a Skin Vapour Pressure Specified

If a boundary condition is applied to the vapour pressure at the skin, the equations for vapour flow are very similar to those for heat flow. Here the correspondences are

$$V_{SK} = P_{SK}$$

$$V_i = P_i \qquad [23]$$

$$V_A = P_A$$

and the charges on the capacitances correspond to the mass accumulation at each point $M_i$. The current sources $I_i$ do not apply as water is only added at the boundaries. Thus, at the first layer

$$\frac{P_{SK} - P_1}{R_{V0}} - \frac{P_1 - P_2}{R_{V1}} = \frac{d}{dt} M_1 \qquad [24]$$

and equations corresponding to [21] and [22] hold at the other N-1 points.

One may calculate the total gain in mass of the clothing system, $M_T$, from the flow into the first layer and out of the last. Thus

$$\frac{P_{SK} - P_1}{R_{V0}} - \frac{P_N - P_A}{R_N} = \frac{d}{dt} M_T \qquad [25]$$

## Equations for Vapour Flow with a Sweat Rate Specified

If the sweat rate rather than the skin vapour pressure is to be specified, $P_{SK}$ becomes a variable and we have

$$M_0 - \frac{P_{SK} - P_1}{R_{VO}} = \frac{d}{dt} M_{SK} \qquad [26]$$

where $M_0$ is the sweat rate and $M_{SK}$ is the mass of water accumulated at the skin. Also equation [25] is modified to include the mass of water at the skin as part of the total accumulation

$$M_0 - \frac{P_N - P_A}{R_{VN}} = \frac{d}{dt} M_T \qquad [27]$$

## Combined Heat and Vapour Flow Equations

The foregoing set of equations may be viewed as a set of first-order ordinary differential equations for the temperatures and masses in which the time derivative of each variable is a function of all the variables. Formally,

$$\frac{d}{dt} \overline{X} = F(\overline{X}) \qquad [28]$$

where $\overline{X}$ is the vector of variables $(T_1, T_2 \text{----} T_N, M_1, M_2 \text{----} M_N, M_T, M_{SK})$ with $M_{SK}$ being included if the boundary condition is on the sweat rate.

Their solution requires that all other quantities, namely $P_i$ and $Q_{Ci}$, be expressed as functions of the T's and M's. This is accomplished as indicated in the preceding section on the general formulation.

The basic assumption is that the vapour pressure within a clothing layer is always in equilibrium with the water that is present as liquid or absorbed on the fibres. If we have a mass of absorbed water plus vapour $M$ and a fabric of mass $M_F$ then we have from equation [10]

$$M = \left\{ C_V + \gamma M_F / P_S(T) \right\} P \qquad [29]$$

or at each point

$$P_i = \frac{M_i}{C_{Vi} + G_i/P_S(T_i)}$$  [30]

with $G_i$ being given by the regain parameter $\gamma$ for the fabric material times the mass of the clothing layer.

In the presence of liquid water we have

$$P_i = P_S(T_i)$$  [31]

the maximum possible value.

Equations [30] and [31] combine to express the vapour pressure in the desired form as a function of temperature and mass

$$P_i = \min \left\{ P_S(T_i), \frac{M_i}{C_{Vi} + G_i/P_S(T_i)} \right\}$$  [32]

Lastly it is necessary to express the rate of heat liberation due to condensation, $Q_c$, as a function of temperature and mass. At each point we have a mass accumulation rate

$$\frac{d}{dt} M_i = \frac{P_{i-1} - P_i}{R_{Vi-1}} - \frac{P_i - P_{i+1}}{R_{Vi}}$$  [33]

If liquid water is already present this mass will also become liquid since P is at its maximum value. Thus (suppressing the subscript i)

$$Q_c = H \frac{dM}{dt}$$  [34]

with $\frac{dM}{dt}$ as in equation [33] and H the latent heat of vaporization of water.

If liquid water is not present then the extra water will accumulate partly as vapour and partly absorbed by the fibres, equilibrium between the two being maintained. Since P and M are related by equation [30] we have

$$\frac{dP}{dt} = \frac{\frac{dM}{dt}}{C_V + G/P_S(T)}$$  [35]

Since the mass of absorbed water is

$$M_A = GP/P_S(T) \qquad\qquad [36]$$

we have

$$\frac{d}{dt} M_A = \frac{G}{P_S(T)} \frac{dP}{dt} \qquad\qquad [37]$$

The heat being liberated is the heat of sorption times the increase in absorbed mass

$$Q_c = H \frac{d}{dt} M_A \qquad\qquad [38]$$

(Here the heat of sorption is taken as the heat of vaporization of free water which may introduce some error at low regain in highly hydrophilic materials).

Combining [36], [37] and [38] we get the desired result expressing $Q_c$ as a function of T and M

$$Q_c = H \frac{G/P_S(T)}{C_V + G/P_S(T)} \frac{dM}{dt} \qquad\qquad [39]$$

with $\frac{dM}{dt}$ given by equation [33].

Since P has already been expressed as a function of T and M, $Q_c$ is also expressed as a function of the same variables and the complete equation set is cast in the form of equation [28].

The numerical calculations are performed on a Hewlett-Packard 1000 mini-computer programmed in FORTRAN IV. Two versions have been written, one for each type of boundary condition on the vapour flow. The parameters for, typically, 8 clothing layers are read in and an initial temperature distribution is calculated assuming a dry, steady-state heat flow. The initial pressure distribution is taken as a constant throughout the clothing system equal to the ambient humidity. The initial mass distribution is then taken as the equilibrium density at these temperatures and vapour pressures. The boundary conditions of temperature and humidity or sweat rate are under operator control and can be varied as the calculation progresses.

The equations are integrated using a general-purpose code written by Shampine and Gordon (3). Unfortunately this code does not efficiently treat equations that are stiff as these tend to be and so the calculations procede rather slowly, running at approximately real time. However, with a dedicated computer, this does not pose any severe problem. More than eight

clothing layers may be handled but with an increase in computation time.


## MODEL CALCULATIONS


Since the Environmental Protection Section's sweating hot plate is not yet operational it was decided to test the numerical model against results published in the open literature. In 1962 Woodcock (1) reported experiments performed on a sweating hot plate covered by wool or polyester fabrics in which the humidity between the clothing and the plate was abruptly changed from its ambient value to saturation. This was accomplished by placing a polyethylene sheet immediately on top of the wet plate, allowing steady-state conditions to be established and then quickly removing the polyethylene exposing the clothing to the wet surface. The heat required to keep the plate at a constant temperature was monitored continuously. After 100 minutes the polyethylene was replaced and the heat loss monitored for another 100 minutes.

With a polyester fabric in place, nothing unexpected occurred. The heat loss from the plate rose from its dry steady-state value to a new steady value when the wet surface was exposed and returned quickly to the dry value when the polyethylene sheet was re-introduced. In the case of wool clothing layers, however, an initial rapid rise to a peak value well above the wet steady-state heat loss was observed followed by a return to the wet steady-state rate. When the polyethylene was re-introduced the heat loss remained high and only gradually returned to its dry steady-state value. These data are reproduced in Figure 3.(along with the results of the model calculations described below).

Woodcock explained the surprising existence of this initial peak as follows. When the polyethylene was first removed the dry fabric was now adjacent to air saturated with water. Therefore a large vapour pressure gradient existed in the immediate vicinity of the wet plate and a high vapour flow, and hence evaporative heat loss from the plate, occurred. With polyester fabric this high gradient was rapidly diminished by the diffusion of water vapour but with wool fabric in place the fibres tended to absorb the water vapour and maintain the high pressure gradient for a longer period of time. After the sheet was replaced, this water absorbed by the wool would evaporate maintaining the heat flow above the dry steady-state value.

To check his explanation Woodcock measured the temperature of the clothing layer adjacent to the plate and found that it rose as water vapour was absorbed liberating heat. These results are reproduced in Figure 4.

It is not possible to exactly reproduce Woodcock's experiment theoretically since he did not report his experimental parameters in sufficient detail, describing the wool clothing for example as simply four

layers of wool shirting material. The calculation, therefore, was performed
with guesses about the unreported quantities such as fabric mass, thickness,
resistance, etc. Exact numerical agreement is therefore not expected but
qualitatively the calculation can be expected to, and does, reproduce the
observed heat loss and the times required for steady-state conditions to be
established are of the correct order.


## CLOTHING PARAMETERS


The model clothing system is taken to consist of:

(1)       A 5-mm air gap of thermal resistance given by the expected heat
flow by conduction in perfectly still air plus the radiative heat flow between
two perfectly black surfaces. The vapour resistance is taken as that of
perfectly still air with a vapour conductivity of $1.8 \times 10^{-10}$ kg/s $m^2$ Pa.

(2)       8 layers of fabric each 1 mm thick with vapour conductivities half
that of still air and heat conductivity of twice the still air value. Thus
the heat and vapour resistance of each layer are 0.021 $m^2$ K/W and $1.1 \times 10^7$
$m^2$ Pa s/kg respectively. Taking a mass for each layer of 0.075 kg/$m^2$ and the
specific heat of polyester as representative, then each layer has a heat
capacity of 78 J/$m^2$K. Calculations were performed for layers of polyester or
wool assumed to be identical except for their hygroscopic properties. The
regain parameter $\gamma$ was calculated from the 65% RH regains for polyester and
wool of 0.4% and 18% respectively.

(3)       A second still-air layer between the clothing and the ambient air
with the same properties as the first.


All of these values are, of course, quite arbitrary, but they are
realistic enough for illustrative purposes.


## RESULTS FOR VARYING SKIN WETTEDNESS


The first set of calculations, reproducing Woodcock's experiment,
are shown in Figures 3 and 4. The temperature of the hot plate is maintained
at 33°C with ambient conditions of 15°C and 12% RH. At t=0 the humidity at
the plate is raised abruptly to 100% and held there for 100 minutes. After
this the boundary conditions are changed to restrict the mass flow from the
plate to zero, simulating the insertion of the polyethylene sheet.
Calculations are shown for both wool and polyester layers and compared to
the experimental results for wool. Since Woodcock's paper does not quote
heat loss on a unit area basis the experimental data have been scaled to
give the same wet steady-state heat loss as the calculations.

The calculation predicts the high initial peak observed in the experiment with wool for both wool and polyester but it is much narrower in the case of polyester. The return of the total heat loss to its steady-state value is predicted to be much faster than observed but this may well be due to the response time of Woodcock's apparatus.

The total heat flow comes to its steady-state value within 1000 s but the system does not achieve steady state as quickly as this as can be seen from the curves of the conductive and evaporative contributions to the total. These take about 5000 seconds to come to their steady-state value. This point is discussed in detail below.

After the water is switched off the experiment and calculated heat flows for wool drop off very slowly as the absorbed water evaporates. The calculation for polyester gives a steady additional heat loss for about 1000 s before dropping rapidly to the dry steady-state heat loss. This is due to the slight accumulation of liquid water in the polyester to an amount of about $0.027$ kg/m$^2$. The total accumulation of water in the wool is $0.14$ kg/m$^2$, mostly absorbed by the fibres.

In Figure 4 the temperature calculated for the second clothing layer is compared to the experimental results. The calculation for wool reproduces the observed temperature changes very well although the actual temperatures differ by several degrees, presumably since the actual position of the thermometer in the experiment is not precisely that assumed in the calculation. All three curves show an initial rise, due to the heat liberated from water that is condensing or being absorbed, followed by a return to a new steady-state value. The temperature change is much smaller and the return to steady-state much faster for polyester than for wool due to the much smaller absorption of water vapour. After the water is switched off there is a decrease in temperature due to the evaporation of the absorbed or condensed water.

The different behaviour of wool and polyester after the water is switched off is not surprising. One would expect a hydrophilic fibre such as wool to soak up more water than a hydrophobic material such as polyester during prolonged periods of sweating and so take longer to dry when sweating ceases. Thus the phenomenon of "post-exercise chill" is expected to be more important in wool clothing than polyester. The initial transient behaviour when the sweat is switched on, however, is not as readily understood intuitively. The heat loss into wool clothing during this transitory period is higher than that into polyester. Spencer-Smith (4) has argued by means of a simple graphical calculation that this must be so and his conclusions are born out by the more detailed calculations, although the time during which these conclusions hold is rather short (about 200 s).

No physiological importance, however, should be attached to this higher initial heat loss into hydrophilic clothing. It is a consequence of the artificial way in which the boundary conditions are set. To get this high initial heat loss it is necessary that the quantity of water available for evaporative cooling be unlimited. This is not physiologically realistic as the sweat glands only secrete water at a finite rate. If the same calculations are performed with boundary conditions on the sweat rate rather than on the vapour pressure at the skin, the conclusions are quite different.

Figure 5 shows the results of calculations performed assuming a finite sweat rate. The value chosen is the same as the steady-state evaporation rate found in the previous calculations ($3.66 \times 10^{-5}$ kg/s m$^2$, equivalent to an evaporative heat loss of 88 W/m$^2$). For polyester clothing the heat loss rises rapidly to its wet steady-state value whereas for wool clothing the heat loss rises very slowly and is everywhere less than that for polyester. The behaviour after the sweat is switched off is as before. From these curves it may be expected that for a man who alternates vigorous exercise with periods of rest, the polyester clothing gives a higher heat loss during exercise and a lower heat loss during the periods of rest and is therefore more effective in avoiding both overheating and excessive cooling.

One final feature of these results is worthy of comment. This is the rapidity with which the total heat loss in Figure 3 achieves its wet steady-state value despite the fact that a considerably longer time is required before truely steady-state conditions are established. To understand this effect consider the total heat flow at any point under steady-state conditions

$$Q_T(x) = -k_H(x)\frac{dT}{dx}(x) - Hk_V(x)\frac{dP}{dt}(x) \qquad [40]$$

Since no heat is accumulating at any point, $Q_T(x)$ is a constant, hence, as *was pointed out by Woodcock (5), one may integrate equation* [40] from one side of the clothing system (x=0) to the other (x=D).

$$\int_0^D Q_T(x)dx = -\int_0^D k_H(x)\frac{dT}{dx}(x)dx - H\int_0^D k_V(x)\frac{dP}{dx}(x)dx \qquad [41]$$

If $Q_T(x)$ is constant and if also $k_H(x)$ and $k_V(x)$, the thermal and vapour conductivities, do not vary through the clothing system, [41] becomes

$$Q_T\int_0^D dx = -k_H\int_0^D dT - Hk_V\int_0^D dP \qquad [42]$$

Integrating

$$Q_TD = -k_H\{T(D)-T(0)\} - Hk_V\{P(D)-P(0)\} \qquad [43]$$

or

$$Q_T = \frac{k_H}{D} \left\{ T_{SK} - T_A \right\} + H \frac{k_V}{D} \left\{ P_{SK} - P_A \right\}$$
[44]

Thus the total heat flow depends only on the fixed temperatures and humidities at the plate and of the ambient air and is insensitive to the detailed temperature and pressure distributions within the clothing layers and to whether or not condensation is occurring. It must be emphasized that the validity of equation [44] depends on the assumption that $k_H$ and $k_V$ do not vary with x and that no heat is accumulating at any point. (One may obtain the commonplace results similar to equation [44] with $k_H/D$ and $k_V/D$ replaced by the total heat conductance and total vapour conductance respectively even if the conductivities are not constant but only if the possibility of condensation or evaporation within the clothing is excluded).

For the model clothing system used in the calculations, the heat and vapour conductivities are not constants but they do not vary greatly. The largest variation is in $k_V$ which is twice as large in the airgap as in the fabric. Furthermore, after the first high heat loss, the temperatures within the clothing are varying only slowly so that there is little accumulation of heat at any point. Therefore the requirements of equation [44] are roughly satisfied and the total heat flow is close to its steady-state value even though the separate conductive and evaporative heat flows are still varying substantially.

In the more realistic model calculations shown in Figure 4, the vapour pressure at the plate is not fixed and so equation [44] cannot be applied and the total heat flow approaches steady-state at the same rate as the other variables.

## RESULTS FOR VARYING AMBIENT CONDITIONS

An advantage is often attributed to hygroscopic clothing in that when the wearer passes from a warm dry environment to one that is cold and wet the clothing can be expected to absorb water and liberate heat thus reducing the heat loss in the humid environment to below that experienced by a wearer of non-hygroscopic clothing. The significance of this "buffering" effect" depends on the heat that is released being substantial and being released rapidly enough to give a power level comparable in magnitude to the extra heat loss rate experienced in the cold environment.

To estimate the significance of this effect, calculations were performed using the same model clothing as previously for a person who is not sweating and has been at steady-state in an atmosphere of 20°C and 50% RH who then moves outside into an atmosphere of 0°C and 90% RH in one case and of 10.9°C and 90% RH in another. These temperatures and humidities are quite arbitrary except for the figure of 10.9°C which was chosen to give the same absolute humidity at 90% RH as in the 20°C and 50% RH environment.

The results are shown in Figure 6.  Some small effect is predicted
by the calculations.  In the 10.9°C case the total heat loss rises rapidly
from its initial steady-state value of 32 $W/m^2$ to about 50 $W/m^2$ and then very
slowly, over the space of several hours, approaches the final steady-state
loss of 55 $W/m^2$.

In the 0°C case the initial rapid rise is to 83 $W/m^2$ about 1.5 $W/m^2$
above the final value.  The effect in this case is an enhancement of heat
loss due to desorption of water.  This may be understood as follows.

In both cases the temperature of the clothing decreases as it is
moved from the warm environment to the cold.  In the 10.9°C case the absolute
humidity in the clothing remains constant and so the relative humidity in-
creases and the clothing absorbs water vapour, liberating heat.

In the 0°C case, the absolute humidity within the clothing decreases
sufficiently to overcome, on average, the effect of the decrease in temper-
ature on the relative humidity, the relative humidity drops, on average, and
the clothing gives up water to the atmosphere, losing heat.  In both cases
the time scale over which the heat of sorption is dissipated is too long for
the heat loss rate to be greatly altered.  Thus, for this model clothing
system at least, the effect, buffering or otherwise, is of little
physiological significance.

## CONCLUSIONS

The models presented in this paper are far from complete in that
they ignore many factors that are of relevance to the performance of clothing.
They do, however, enable the influence of some of the differences among
clothing materials to be understood in a quantitative way.  The results
presented here suggest that, other factors being constant, non-hygroscopic
clothing is better in maintaining an even body temperature than is hygro-
scopic.  The difference between hygroscopic and non-hygroscopic clothing
materials is not evident from steady-state calculations and measurements
alone and erroneous conclusions may be drawn from the inappropriate use of
sweating hot plates that are constantly wet as well as from calculations
assuming a constantly wet skin.

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   (Butterworths Publications and The Textile Institute), p. 89 (1960).

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   Differential Equations.  The Initial Value Problem".  W.H. Freeman and
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5. A.H. Woodcock.  U.S. Army Office of the Quartermaster General.
   Environmental Protection Section, Report No. 170 (1950).
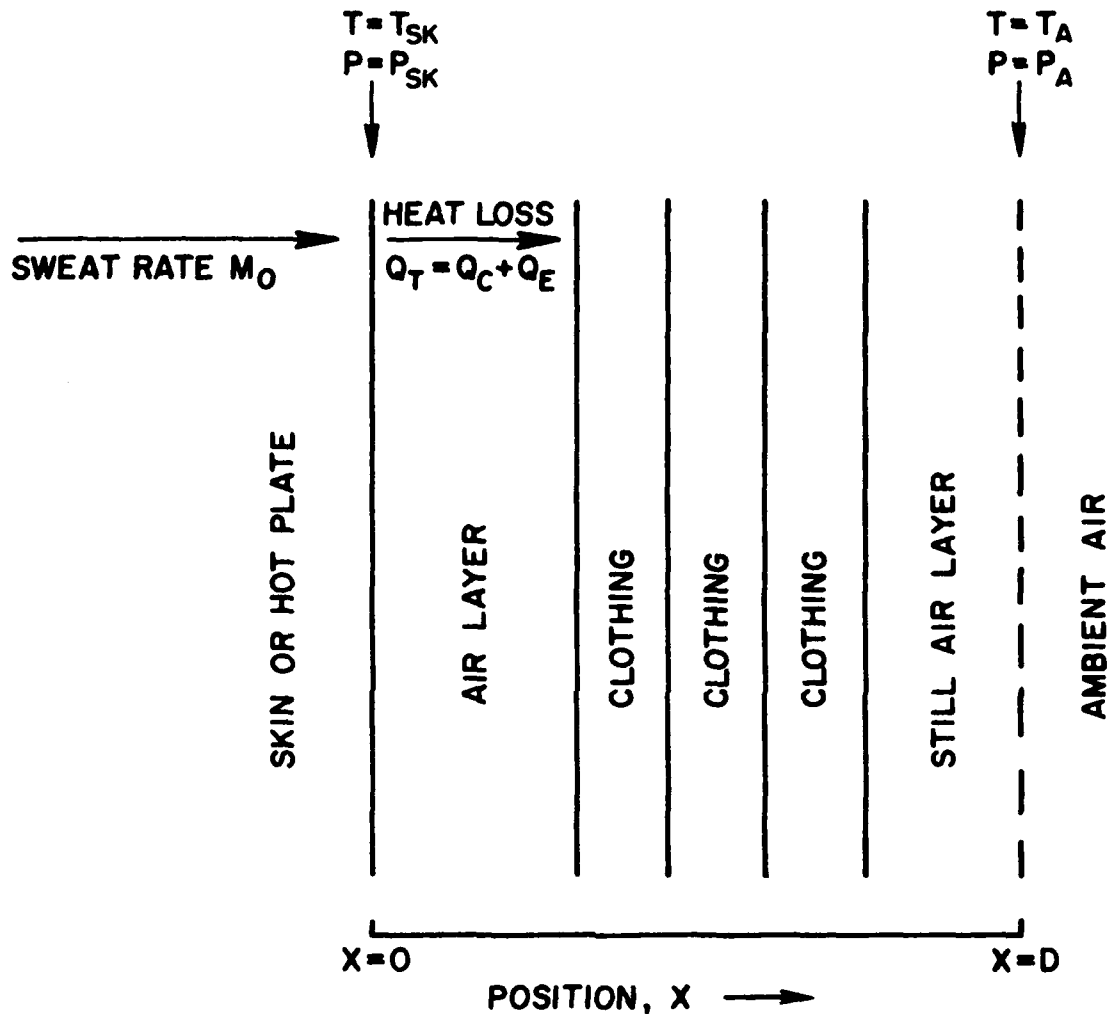
Figure 1:   A sweating hot plate or flat area of skin is covered
            by several layers of clothing and still air.  At the
            ambient air, a temperature and vapour pressure are
            specified.  At the plate, a temperature and vapour
            pressure or a sweat rate is specified.  The total heat
            loss from the plate includes conductive and evaporative
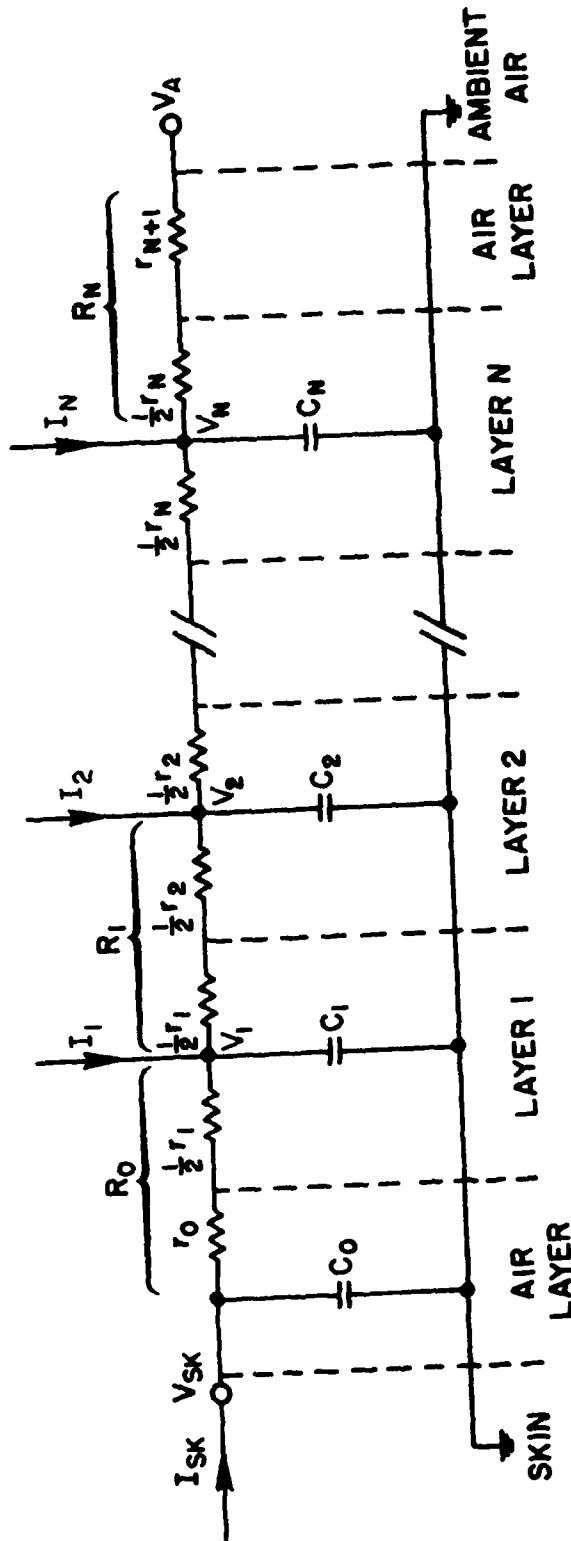            contributions ($Q_C$ and $Q_E$).

Figure 2: Equivalent electrical network for the numerical calculations. Each clothing or still air layer is represented by a resistance and a capacitance (either thermal or vapour). The voltages correspond to temperatures or pressures, the charges on the capacitors to accumulated heat or water. The current source $I_{SK}$ corresponds to a sweat rate, the $I$'s to heat liberated by condensation or absorption of water vapour.
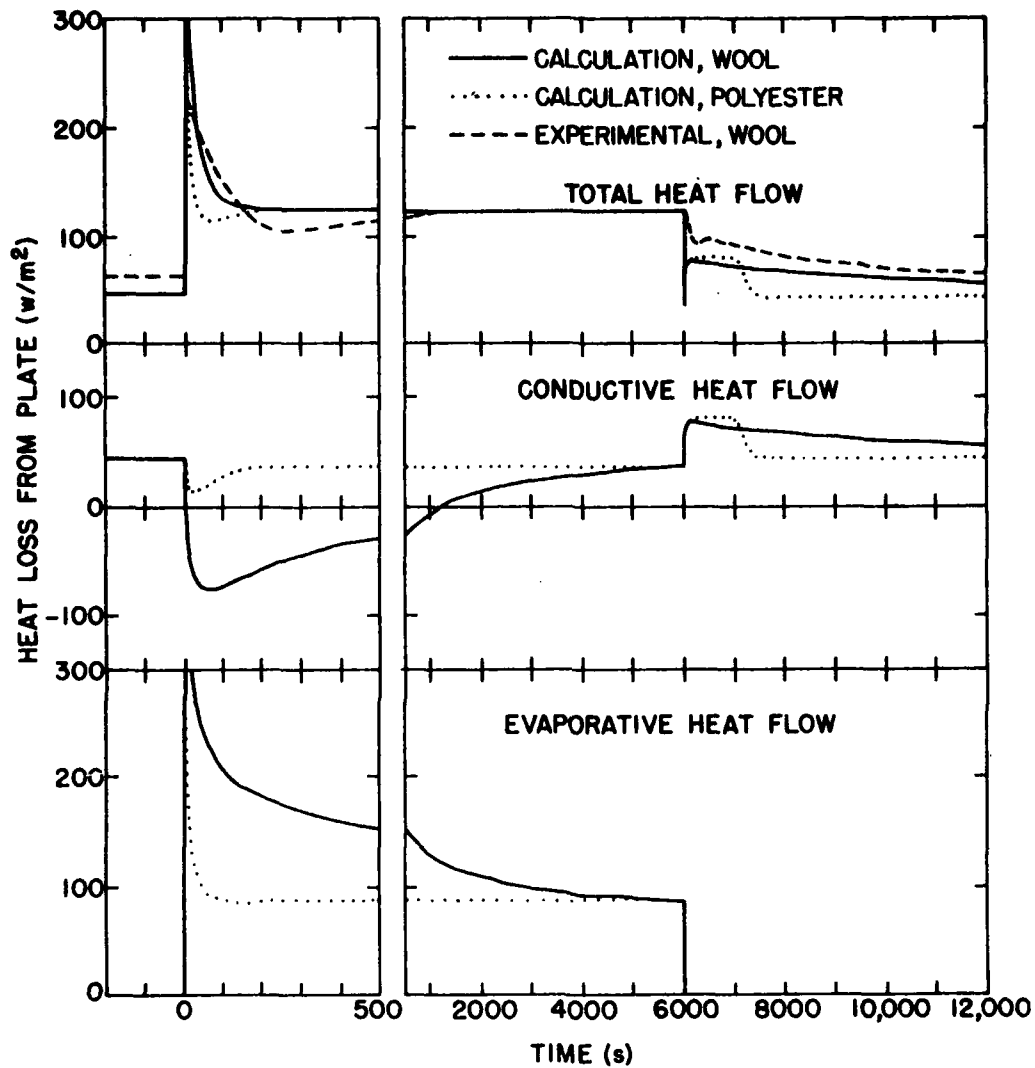
Figure 3:  Calculations of the heat flow from the plate when the vapour
           pressure at the plate is varied.  The ambient conditions are
           15°C and 12% RH.  The plate temperature is held at 33°C.
           Before t=0 the plate humidity is that of the ambient.  From
           t=0 to t=6000 s the plate is saturated with water.  After
           t=6000 s the sweat rate is held to zero.  The conductive and
           evaporative heat flows which make up the total are shown
           separately.

           This calculated total heat flow for wool clothing is in good
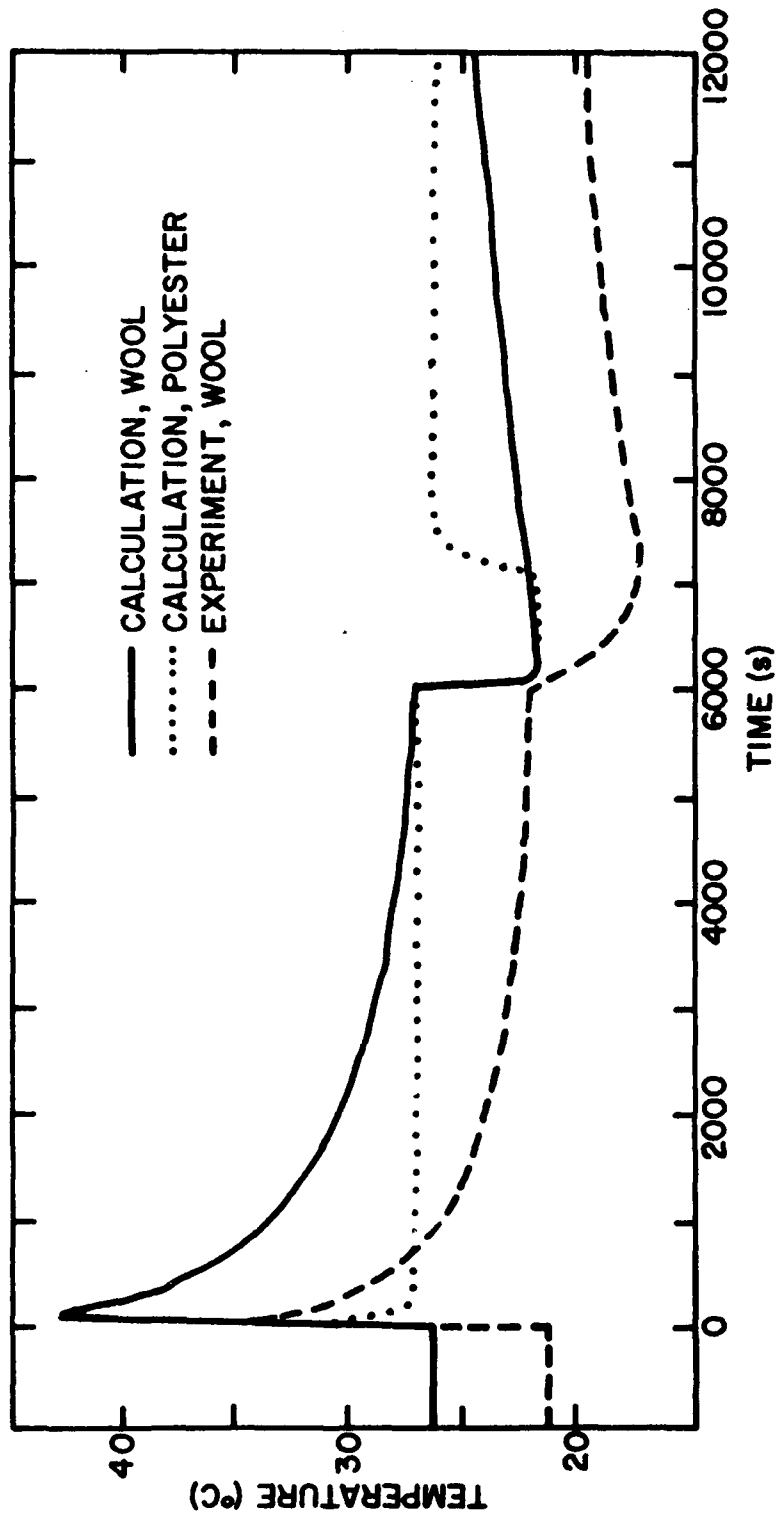           agreement with the experiments of Woodcock (1).

Figure 4: The temperature of the second of 8 layers of clothing in the same calculation as in Figure 3. The results for wool show the same behaviour as observed by Woodcock. The changes in temperature are due to the absorption or condensation of water vapour and its subsequent evaporation.
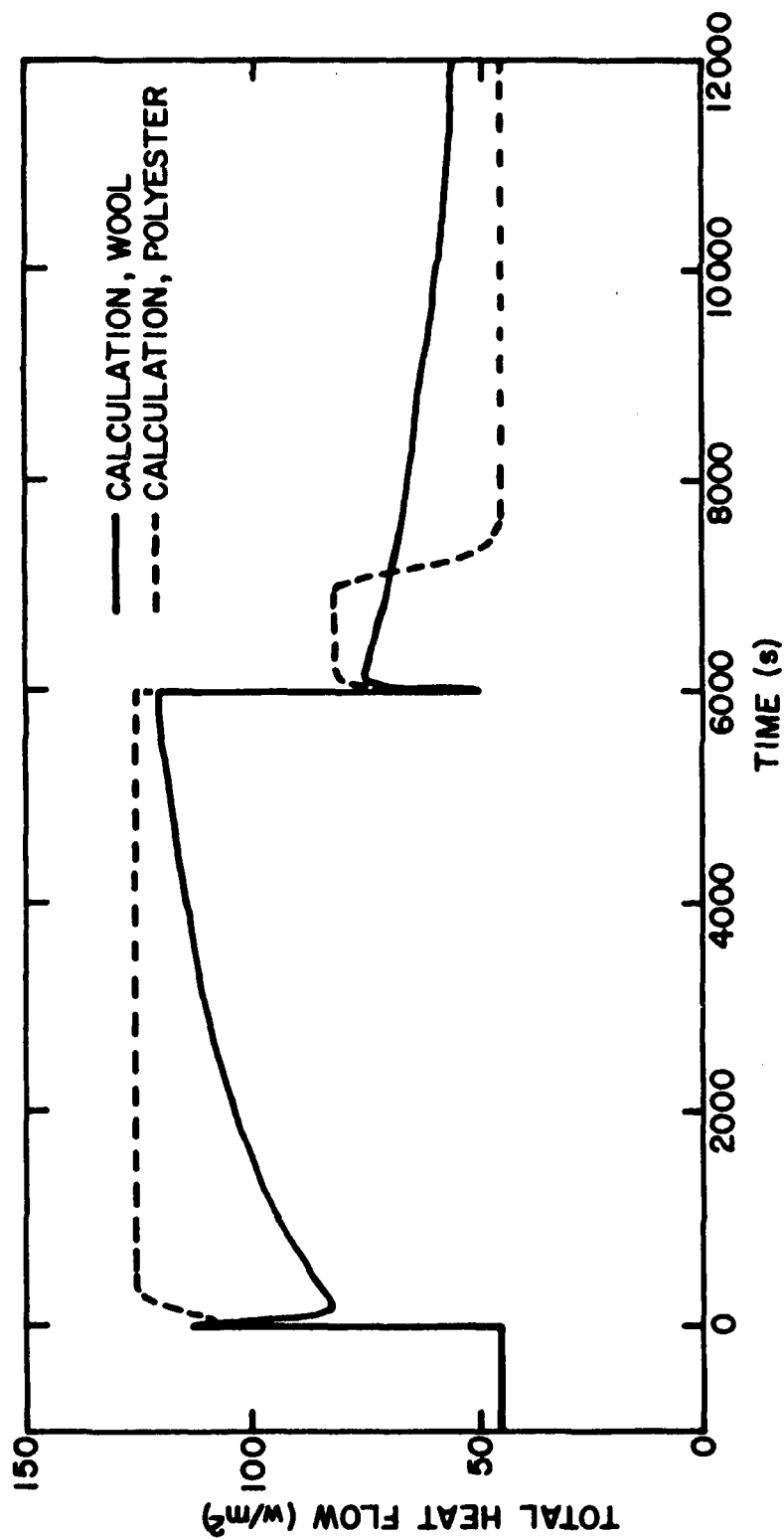
Figure 5: A similar calculation to that shown in Figure 3 but with a sweat rate rather than a plate vapour pressure specified. The heat loss from wool clothing approaches its steady-state value very slowly.
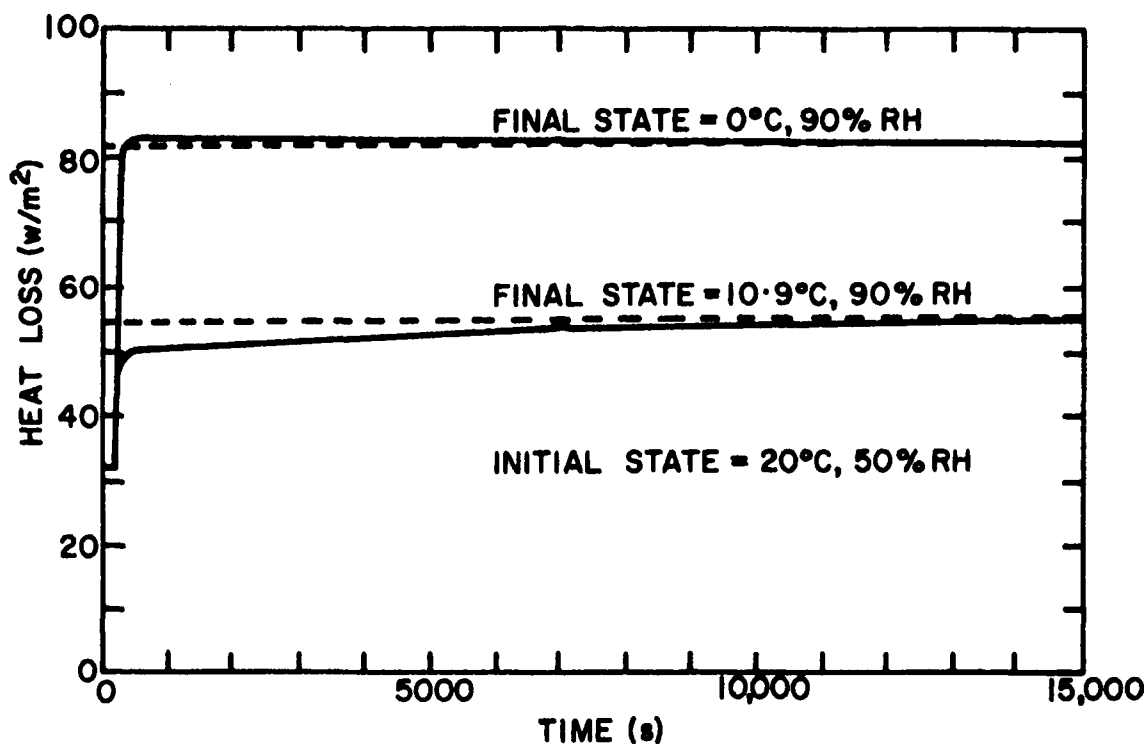
Figure 6:   The heat loss from a dry plate into wool clothing
            when the ambient atmospheric conditions are varied.
            For a 10.9°C final state the absolute humidity is
            the same as that of the initial state and the heat
            loss is less than its steady-state value.  In the
            0°C final state the absolute humidity is less than
            that of the initial state and the heat loss exceeds
            the steady-state value.

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13. ABSTRACT

A numerical model of heat and water-vapour transport through multi-layered clothing systems under transient conditions is presented. Taken into account are the condensation and evaporation of liquid water within the clothing layers and changes in the amount of water absorbed by hygroscopic fibres although the hygroscopic properties are taken to be of a very simple form. The calculations are compared to experiments reported by Woodcock in 1962, giving good agreement, and used to discuss the so-called buffering effect of hygroscopic clothing materials.

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