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USE OF A WETTED COVER TO REDUCE HEAT STRESS IN IMPERMEABLE CLOT--ETC(U)

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USE OF A WETTED COVER TO REDUCE HEAT STRESS IN IMPERMEABLE CLOTHING

US ARMY RESEARCH INSTITUE OF ENVIRONMENTAL MEDICINE

Natick, Massachusetts

OCTOBER 1980

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Technical Report

No. T 7/80

Use of a Wetted Cover to Reduce Heat Stress in Impermeable Clothing

by

John R. Breckenridge

Project Reference 3E162777A845

October 1980

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A

Abstract

A mathematical model based on physical relations for heat exchange between clothed man and his environment has been developed which describes the cooling effect of a wet cover worn over an impermeable ensemble, in terms of the ensemble characteristics and the ambient environment. The model has been validated at low air movement for one such ensemble by comparing predictions of increased skin heat loss and cover evaporation with values obtained using an electrically heated copper manikin dressed in the ensemble, with the cover both dry and wetted. The model predicts for this ensemble supplementary cooling (increased skin heat loss) ranging from 40 watts at 35°C, 70% relative humidity, and low air movement to almost 200 watts for a hot/dry environment of 50°C, 20% r.h., with 5 meters/second wind. Predicted water requirements to maintain the cover wet under these conditions range from 0.2 kg/hr to 1.9 kg/hr. The model also reveals that the wet cover would reduce the heat load imposed on a man by sunlight by 20 to 40 watts in full sun, but with a 0.2 to 0.3 kg/hr increase in water requirements.

Introduction

Studies beginning at Camp Sibert, Alabama in the early 1940's (6), have consistently demonstrated that men wearing chemical protective clothing cannot work for extended periods in the heat. Such clothing, which is characterized by partial or total impermeability to water vapor transfer, seriously impedes sweat evaporation, the prime source of cooling for men in an air temperature above 30°C. Using data from several studies, Custance (5) concluded that the safe time for moderate work in a totally impermeable system is limited to about 1 hour at 27° to 30°C, and 30 minutes or less above 32°C. More permeable systems extend tolerance time somewhat, particularly when worn in an "open" configuration with protective gloves and hood removed. Joy and Goldman (13) studied such a system, consisting of impregnated underwear and fatigues, in Panama in 1963; for wet-bulb globe temperatures (WBGT) (16,22,24) of 29°C, the times for 50% heat casualties of an infantry unit in the attack were about 1-1/2 hours with the men encapsulated ("closed" suit), and about 1-3/4 hours for "open" suit operations. However, the first heat casualties were usually taken during the first hour of the operation.

Various approaches for alleviating this heat stress in chemical protective clothing have been studies (8,12). Most involve increasing the permeability of the clothing to water vapor transfer, to improve its ability to dissipate metabolic heat. The current US Army Standard A Chemical Protective Suit, which employs charcoal impregnated garments for absorption of chemical agent, has relatively high water vapor permeability, and shows promise for extending the duration of effective tactical operations. A second approach is use of battery-operated backpacks to deliver filtered ambient air into an otherwise impermeable clothing system, as currently done in the new Engineer Ordnance Demolition (EOD) suit. This air flow enhances evaporative cooling and can extend tolerance time by several hours, depending on the activity level and the ambient environment. Auxiliary cooling approaches include ventilation with conditioned air, water-cooled undergarment for direct skin cooling and a head cooling cap (8). These have been investigated as possible approaches but must, however, be viewed as limited to special situations where the wearer is in or around a vehicle; they would not be applicable for the infantryman.

A final approach, use of a wettable cover over an impermeable garment, is less well defined with regard to the environments and activity levels for which it would be applicable. Although used with some success on the Toxicological Agent Protective (TAP) suit, the concept has apparently been discarded by the US, since the terry cloth cover for the TAP suit is no longer listed in the latest pamphlet on Protective Clothing and Equipment (DA PAM 385-3, Rev. 1976). Nevertheless, the approach appears to have merits since the only auxiliary equipment needed is an ample supply of water.

In this paper, a physical model is described which predicts the cooling benefits, at skin level, from a wetted cover on an impermeable ensemble, in terms of the ensemble heat transfer characteristics and such environmental factors as air temperature, humidity and wind speed. Tentative validation of the model has been accomplished using the results of wet-cover experiments on an electrically heated copper manikin. Finally, predictions based on the model are presented which provide estimates of increased body heat dissipation in various environments, for an ensemble including fatigues, an impermeable layer, and a wettable cover.

Theory

An increase in skin heat dissipation can be produced by evaporating water from a wet cover on a clothing system. The increase depends on at least four factors: a) the external air movement, b) the ambient air vapor content, c) the coverage of the wetted layer, and d) the insulation between it and the wearer's skin. The first three factors influence the evaporation rate and the amount of heat absorbed in the process. The last factor, the ensemble insulating value, influences the ratio of cooling available to the skin compared to total cooling; i.e., the amount of skin cooling per kilogram of water evaporated. For a typical ensemble under relatively calm conditions the cooling efficiency (i.e., the cooling benefit divided by the heat absorbed from the cover) is 20 to 30%; this efficiency decreases with air movement, and is less than 15% in a 5 m/s wind. These low efficiencies with increasing air movement result because evaporation lowers the temperature of the cover, sometimes below ambient temperature, and hence alters the sensible (associated with temperature differences) heat exchange with the environment. Consequently, the net cooling is the evaporative heat loss reduced by the change in sensible loss, which can be quite high.

The ratio of cooling at skin level to evaporative heat loss from the cover for the condition where the man is not sweating and the layers inside the cover are dry, is derived from an equation originally given by Burton (4) for auxiliary heating. This ratio, called F_{cl} by Nishi (18), may be termed a cooling efficiency, i.e.,

$$\text{Efficiency} = \frac{I_a}{f_{cl}\, I_{tot}} \qquad \text{Equation 1}$$

where I_a is the boundary air layer insulation for a nude man, I_{tot} is the combined insulation of clothing plus its boundary air layer, and f_{cl} is the ratio of clothing surface to skin surface areas. This factor (f_{cl}) adjusts the clothing boundary layer insulation to account for the increased clothing surface area available for heat transfer (7); i.e., the insulation of the clothing boundary air layer based on skin surface area is I_a/f_{cl}. Accordingly,

$$I_{tot} = I_{cl} + I_a/f_{cl} \qquad \text{Equation 2}$$

where I_{cl} is the intrinsic insulation of the clothing (19). Equation 1 is not applicable where the man is sweating, since no account is taken of evaporative heat exchanges occurring within the clothing.

In the theoretical development which follows, a mathematical expression, based on physical relationships for sensible and evaporative heat exchanges, is derived which permits close approximation of the cooling benefits from evaporation at the clothing surface. This development applies specifically for clothing systems in which an impermeable layer is located directly beneath a thin wettable cover on the outside, i.e., where the site of evaporation is accurately defined. Additional clothing layers may or may not be present under the impermeable barrier. These layers may be dry or wet, and the man may be sweating.

The rate of evaporative heat loss from the wetted cover is determined by the relationship:

$$H_e = A_{sk} f_{cl} w h_e (p_c - \phi_a p_a) \qquad \text{Equation 3}$$

where: H_e = evaporative heat loss rate (W)

A_{sk} = skin surface area (m^2)

w = wet fraction of clothing surface (%)

h_e = coefficient of evaporative heat loss (W/m^2 mm Hg)

p_c = water vapor pressure at cover surface (mm Hg)

p_a = saturated water vapor pressure of air at ambient temperature (mm Hg)

ϕ_a = ambient relative humidity (%)

In this equation (A_{sk} f_{cl}) is the total clothing surface area and (A_{sk} f_{cl} w) is the wetted cover area. The coefficient h_e is a function of ambient air motion and is related to the coefficient of convective heat transfer at the clothing surface according to the "modified Lewis relation" (20); this governing relation for water at one atmosphere pressure is:

$$h_e = 2.2\, h_c \qquad \text{Equation 4}$$

where the constant 2.2 has units ^oC/mm Hg and h_c is the coefficient of convective heat exchange, $W/m^2\ ^oC$. The vapor pressure at the cover surface (p_c) is assumed to be the saturated value at the average cover temperature T_c.

For the man in the field, the value of H_e cannot be readily established from Equation 3 since T_c is not known. However, T_c can be estimated by writing an equation which describes all the heat gains and losses at the clothing surface; i.e., a complete heat balance can be developed. The applicable equation with a wet cover is:

$$H_r + H_c + H_e + H_{sk} + H_s = 0 \qquad \text{Equation 5}$$

where: H_r = net radiant heat gain from surroundings (W)

H_c = heat gain from ambient air by convection (W)

H_{sk} = heat received from the skin (W)

H_s = solar radiation absorbed at clothing surface (W)

In this balance, heat gains are considered positive. It is, therefore, necessary to redefine H_e so that an evaporative loss is negative; this can be done simply by writing the vapor pressure gradient in Equation 3 as ($\phi_a\, p_a - p_c$) instead of ($p_c - \phi_a\, p_a$), i.e.:

$$H_e = A_{sk} f_{cl} w h_e (\phi_a\, p_a - p_c) \qquad \text{Equation 6}$$

Each of the terms in Equation 5 except H_s is dependent on an average clothing surface temperature $\bar{T}_{cl}$. Therefore, $\bar{T}_{cl}$ may be estimated by substituting the expressions which describe these terms into Equation 5. The factor H_s is independent of $\bar{T}_{cl}$, and is a constant for any given set of conditions; a simplifying assumption relating T_c to $\bar{T}_{cl}$, which is required in handling H_e, will be discussed later.

Once the value for $\bar{T}_{cl}$ has been established, the calculation of the cooling benefit of a wet cover is straightforward. This cooling benefit is simply H_{sk} with wet cover minus H_{sk} with the cover dry. This latter value may be obtained by setting H_e in Equation 5 equal to zero.

Equation 5, written for both the wet and dry cover conditions, with the skin and inner clothing layers dry, is the basis for Burton's efficiency factor (cf. Equation 1) as applied to the additional skin cooling with a wet surface covering.

Relationships for $H_r + H_c$:

Assuming, for simplicity, that the mean radiant temperature of the surroundings equals air temperature, the sensible heat term ($H_r + H_c$) may be expressed by the equation:

$$H_r + H_c = A_{sk}\, f_{cl}\, (h_r + h_c)\, (T_a - \bar{T}_{cl}) \qquad \text{Equation 7}$$

where: h_r = linear coefficient of radiant heat exchange ($W/m^2\ ^oC$)

h_c = coefficient of convective heat exchange ($W/m^2\ ^oC$)

T_a = ambient air temperature (^oC)

$\bar{T}_{cl}$ = mean clothing surface temperature (^oC)

The radiation coefficient (h_r) depends on the average of the surface and air temperatures, the percent of clothing surface area involved in the radiation exchange, and the emissivity of the surface. Both air and surface temperatures will vary but, for simplicity, h_r will be assumed constant at a value of $4.6\ W/m^2\ ^oC$. This assumption will not result in serious error since the practical range of air temperatures requiring a wetted cover would be limited to about 20 degrees. Considering all factors, h_r would not be expected to vary by more than 20%; the maximum inaccuracy in h_r can be limited to about 10% by choosing this value of $4.6\ W/m^2\ ^oC$, which applies for an average of cover and air temperatures of about 35^oC.

The convection coefficient (h_c) is determined primarily by the effective air movement over the clothing surface. Several relationships between h_c and air movement have been published. However, a recent relationship developed by Mitchell (17) for standing men appears to agree closely with results obtained locally using a heated copper manikin, and will be used for expressing h_c in this paper:

$$h_c = 8.3\ V^{0.6} \qquad \text{Equation 8}$$

where V is the combined air movement from subject motion and ambient wind, in m/s.

The insulation value of the boundary air layer (I_a) at the clothing surface (in $^oC\ m^2/W$) is simply the reciprocal of ($h_r + h_c$). The two coefficients are essentially the same as for nude man, for whom boundary layer insulation is designated as I_a; the only adjustment required is for the altered surface area with clothing. Equation 7 may consequently be rewritten in the form

$$H_r + H_c = \frac{A_{sk}(T_a - \overline{T}_{cl})}{I_a/f_{cl}} \qquad \text{Equation 7(a)}$$

where the clothing boundary layer insulation is I_a/f_{cl}, as noted earlier. Expressed in clo units (9), I_a is given by:

$$I_a = \frac{6.46}{(h_r + h_c)} = \frac{6.46}{4.6 + 8.3V^{0.6}} \qquad \text{Equation 9}$$

where the constant 6.46 converts $^oC\ m^2/W$ to clo units. From this equation, I_a is 0.75 clo for an air motion of 0.3 m/s, which is within 0.01 clo of the value measured with a standing copper manikin (0.76 clo) under this air movement.

Relationships for H_e:

The basic equation for determining H_e *is a combination of Equation 6 with* Equation 4; i.e.:

$$H_e = 2.2\ A_{sk}\ f_{cl}\ w\ h_c\ (\phi_a\ p_a - p_c) \qquad \text{Equation 10}$$

The wetted fraction (w) of the clothing surface was estimated at 0.8 (80%) for the ensemble used in this study, since the cover did not extend over the essentially impermeable boots, gloves, or mask. Deduction of 11%, 6%, and 3%, respectively, were made for these dry-surface areas.

To avoid introducing undue complexity in deriving an equation for clothing surface temperature, a simplifying assumption has been made that the mean temperature of the wet cover equals mean surface temperature $\overline{T}_{cl}$, and thus, p_c equals $\overline{p}_{cl}$, the saturated vapor pressure at $\overline{T}_{cl}$, i.e.:

$$H_e = 2.2\ A_{sk} f_{cl} w\ h_c\ (\phi_a\ p_a - \overline{p}_{cl}) \qquad \text{Equation 11}$$

This simplifying assumption introduces an error in the cover vapor pressure p_c, and hence in H_e, since the two temperatures will rarely be equal. Under most conditions the wetted cover temperature will average less than $\overline{T}_{cl}$, because the dry surface areas will not be cooled. Using $\overline{p}_{cl}$ in Equation 11, in place of p_c in Equation 10, will then result in an overestimate of evaporative cooling (H_e will assume too high a negative value). However, this overestimate will not be as great as it appears. Equation 5 shows that, if H_e is overestimated, a corresponding increase in ($H_r + H_c + H_{sk} + H_s$) is required to balance the equation. With constant solar heating (H_s), this means that $\overline{T}_{cl}$ must be lowered to effect the required increase; this reduction in $\overline{T}_{cl}$ will tend to bring it into line with the actual wet cover temperature, thereby reducing the overestimate in H_e.

Since $\bar{p}_{cl}$ is a function of $\bar{T}_{cl}$, a suitable relation between the two must be employed in evaluating H_e. Several expressions, characteristically high order equations, are available which accurately relate saturated vapor pressure and temperature and any of these may be used in a computer solution for $\bar{T}_{cl}$. However, for the narrow range in $\bar{T}_{cl}$ found in a stressful hot environment, a simple equation which can be more easily employed in hand calculations will suffice. Over the range 20° to 35°C, the equation:

$$\bar{p}_{cl} = 5.524\, e^{0.05828\, \bar{T}_{cl}} \qquad \text{Equation 12}$$

describes $\bar{p}_{cl}$ with an accuracy within 0.3 mm Hg, which is adequate for making a preliminary estimate of $\bar{T}_{cl}$. If desired, this estimate may subsequently be refined by using the published vapor pressure at the estimated $\bar{T}_{cl}$, rather than $\bar{p}_{cl}$ from Equation 12, for the final calculation.

The use of Equation 12 for expressing H_e in Equation 5 results in a final equation for $\bar{T}_{cl}$ which must be solved by iteration. The other variables in Equation 5, except the solar heat (H_s), may satisfactorily be expressed as simple functions of $\bar{T}_{cl}$. However, the appearance of $\bar{T}_{cl}$ as an exponential in Equation 12 prevents a simple grouping of all $\bar{T}_{cl}$ terms for a direct solution.

Relationships for H_{sk}:

With a clothing system containing an impermeable layer, the transfer of heat from a sweat-wetted skin to the clothing surface involves both sensible and evaporative flows up to the impermeable barrier, but only sensible flow between it and the clothing surface. We have shown that evaporative heat transfer between the skin and vapor barrier can occur if the two are at different temperatures, even though there is no net water loss (1). The explanation involves a cyclic process in which heat is absorbed from the skin by sweat evaporation, transferred across the inner insulating layers along with the vapor, and then released when the vapor condenses on the impermeable barrier, which is at a lower temperature than the skin; the condensate subsequently wicks back toward the skin to sustain the cycle. Experimental evidence suggests that the rate of evaporative heat transfer in this process is proportional to the vapor pressure gradient between the skin and impermeable layer, which is the difference in saturated vapor pressures at skin and impermeable layer temperatures, respectively. Beyond the impermeable layer, the flow (H_{sk}) to the clothing surface is of course all sensible heat. Assuming no heat storage at the vapor barrier, this sensible heat flow must equal the sum of the sensible and evaporative flows from the skin to the vapor barrier. Thus, the temperature T_i of the inner face of the impermeable layer may be determined by writing the H_{sk} equations for the two zones.

These two relationships (a and b) are expressed as follows:

(a) The heat flow from the skin to the impermeable layer is:

$$H_{sk} = \frac{6.46\ A_{sk}}{I_{si}} \left[(\bar{T}_s - T_i) + 2.2\ i_m\ (\bar{p}_s - p_i) \right] \qquad \text{Equation 13}$$

where:
I_{si} = insulation between skin and impermeable layer (clo)
$\bar{T}_s$ = mean skin temperature (^oC)
T_i = temperature of impermeable layer (inner face) (^oC)
$\bar{p}_s$ = saturated vapor pressure at $\bar{T}_s$ (mm Hg)
p_i = saturated vapor pressure at T_i (mm Hg)
i_m = moisture permeability index of skin to impermeable layer zone (N.D.)

The evaporative heat transfer coefficient in this equation is $2.2\ i_m/I_{si}$, where the factor 2.2^oC/mm Hg is the "modified Lewis relation" constant introduced earlier (cf. Equation 4) and i_m, which has a range from 0 (no transfer) to 1.0 (theoretical maximal transfer), is the parameter proposed by Woodcock (23) for describing resistance of fabrics to evaporative transfer.

(b) The heat flow from the impermeable layer to the clothing surface is:

$$H_{sk} = \frac{6.46\ A_{sk}}{I_{ic}} (T_i - \bar{T}_{cl}) \qquad \text{Equation 14}$$

where I_{ic} = the insulation (clo) based on the area A_{sk}, from the inner face of the impermeable layer to the clothing surface.

Equating the two expressions for H_{sk}:

$$(\bar{T}_s - T_i) + 2.2\ i_m\ (p_s - p_i) = (I_{si}/I_{ic})\ (T_i - \bar{T}_{cl})$$

or

$$T_i = \frac{\bar{T}_s + 2.2\ i_m\ (\bar{p}_s - p_i) + (I_{si}/I_{ic})\ \bar{T}_{cl}}{1 + (I_{si}/I_{ic})} \qquad \text{Equation 15}$$

The dependency of p_i on T_i in this equation is not as simply handled as was the $\bar{p}_{cl}$ to $\bar{T}_{cl}$ relationship involved in evaluating H_e. As noted, an iterative solution for $\bar{T}_{cl}$ is made necessary by the exponential term containing $\bar{T}_{cl}$ in Equation 12. Equation 12 might also be used to express the relationship of p_i and T_i. However, T_i is related to $\bar{T}_{cl}$ and such a procedure would therefore require iteration for both T_i and $\bar{T}_{cl}$. This might be successfully accomplished with a computer, but certainly not easily with a simple calculator. For this reason, and in view of the limited range over which accurate evaluation of p_i is required, a linear relationship between p_i and T_i has been employed, namely:

$$p_i = 1.917\, T_i - 25.42 \qquad \text{Equation 16}$$

This equation was selected to cause minimal error (less than 0.5 mm Hg) in p_i from 27° to 34°C, the T_i range in which skin-to-impermeable layer evaporative transfer would be a consideration, i.e., important in determining H_{sk} under stressful conditions.

Substituting Equation 16 into Equation 15 provides the following expression for T_i

$$T_i = \frac{\bar{T}_s + 2.2\, i_m (\bar{p}_s + 25.42) + (I_{si}/I_{ic})\, \bar{T}_{cl}}{1 + 4.217\, i_m + (I_{si}/I_{ic})} \qquad \text{Equation 17}$$

which, when substituted into Equation 14 gives:

$$H_{sk} = \frac{6.46\, A_{sk}}{I_{ic}} \left[\frac{\bar{T}_s - \bar{T}_{cl} + 2.2\, i_m (\bar{p}_s + 25.42) - 4.217\, i_m \bar{T}_{cl}}{1 + 4.217\, i_m + (I_{si}/I_{ic})} \right] \qquad \text{Equation 18}$$

Relationships for H_s:

The amount of solar heat (H_s) absorbed at the clothing surface may be estimated using equations which we have previously developed to describe solar heat heat load on man (2,3). These equations separately quantify the contributions of direct, diffuse, and terrain-reflected sunlight in terms of radiation intensity, clothing absorption characteristics, and parameters related to solar angle and posture of the man. Equations are included to account for radiation transmitted directly to the skin via the clothing, but these are not applicable in the present case since direct transmission would be blocked by the impermeable layer. These equations actually predict the heating at skin level, but may be converted to heat absorption at the clothing surface by omitting the Burton efficiency factor (designated by U) from each equation.

Some difficulty will be encountered in predicting or estimating the three solar radiation components for a field operation owing to uncertainty as to cloudiness, effects of shading, terrain reflectance, etc. Preferably the three components should be measured, but this is usually not practical. Estimates of maximal radiation, expressed as a function of major climatic region (e.g., tropical rain forest) have been published for 9 regions by Roller (21). These may be used as guides, assuming a "hazy" clear sky. Values appropriate for heavier cloud cover may be inferred from the experimental data obtained in a typical temperate zone in the eastern United States (2).

Final Prediction Equations:

The equation for predicting $\bar{T}_{cl}$ is obtained by substituting Equation 7, 11, and 18 for ($H_r + H_c$), H_e, and H_{sk}, respectively, in Equation 5, the heat balance with a wet cover. This solution yields the following expression:

$$\bar{T}_{cl} = \frac{(h_r + h_c)\, T_a\, f_{cl} + 2.2\, h_c\, w \phi_a p_a f_{cl} - 2.2\, h_c\, w\, \bar{p}_{cl} f_{cl} + \dfrac{6.46}{I_{ic}} \left[\dfrac{\bar{T}_s + 2.2\, i_m (\bar{p}_s + 25.42)}{1 + 4.217\, i_m + I_{si}/I_{ic}} \right] + H_s}{(h_r + h_c)\, f_{cl} + \dfrac{6.46\,(1 + 4.217\, i_m)}{I_{ic}\,(1 + 4.217\, i_m + I_{si}/I_{ic})}} \qquad \text{Equation 19}$$

The term p_{cl} is evaluated using Equation 12 or other suitable relationship between temperature and saturated vapor pressure.

Once $\bar{T}_{cl}$ has been determined by iteration of Equation 19 the separate terms in Equation 5 may be evaluated using the appropriate equations, namely,

$$H_r + H_c = A_{sk}\, f_{cl}\, (h_r + h_c)\, (T_a - \bar{T}_{cl}) \qquad \text{Equation 7}$$

$$H_e = 2.2\, A_{sk}\, f_{cl}\, w\, h_c\, (\phi_a\, p_a - \bar{P}_{cl}) \qquad \text{Equation 11}$$

$$H_{sk} = -(H_r + H_c + H_e + H_s) \qquad \text{Equation 5}$$

For a dry skin condition, H_{sk} may be directly computed using the equation:

$$H_{sk} = \frac{6.46\, A_{sk}}{I_{cl}}\, (\bar{T}_s - \bar{T}_{cl}) \qquad \text{Equation 20}$$

where I_{cl} is the intrinsic insulation, in clo units, of the entire clothing system. This equation is obtained by summing the insulations I_{si} and I_{ic}, and the temperature gradients $(\bar{T}_s - T_i)$ and $(T_i - \bar{T}_{cl})$ in Equations 13 and 14. The term $(\bar{p}_s - p_i)$ in Equation 13 equals zero when the skin is dry: under these conditions, i_m in Equation 19 may also be considered as zero.

The cooling benefit derived from the wet cover is simply the difference in skin heat loss rate (H_{sk}) with the cover wet and dry, respectively. The wet cover loss is determined using Equation 18 or, for dry skin, Equation 20. The dry cover loss is established by determining $\bar{T}_{cl}$ from Equation 19, with the terms for H_e, namely,

$$2.2\, h_c\, w\, \phi_a\, p_a\, f_{cl} - 2.2\, h_c\, w\, p_{cl}\, f_{cl}$$

eliminated; the loss with a dry skin may then be calculated using Equation 20, and the loss with a wet skin using Equation 5. In the latter case, H_{sk} is simply

$$H_{sk} = -(H_r + H_c + H_s)$$

where $(H_r + H_c)$ is given by Equation 7.

Materials and Methods

Heat loss data for validating the mathematical skin cooling model were obtained using a standing electrically-heated life-size copper manikin covered with a form-fitting cotton "skin" (11). This "skin" could be left dry to represent a non-sweating condition, or completely wetted by spraying with water to simulate a sweating man with a 100% sweat-wetted skin surface. The manikin was dressed in standard tropical combat fatigues, followed by a loose-fitting two-piece impermeable garment with hood which covered all areas except the feet, hands, and face, and then by a wettable cotton layer, also two-piece. The ensemble in addition included: cushion sole socks, combat boots, and ankle-height rubber bootees on the feet; flexible rubber gloves over the hands and wrist; and a standard Army chemical protective mask over the face. The impermeable garment was elasticized at the ankles, wrists, and around the facial opening to provide a tight seal; it was worn outside the tops of the combat boots and the wrist gauntlets on the gloves, and covered the edges of the mask. The wettable outer cover provided similar coverage except that the bottoms of the trousers extended just to the top of the combat boots, well above the impermeable layer elastic seals. The trouser legs, sleeves, and neck opening on the cover were generously cut, and were thus not in close contact with the impermeable layer, so that air could freely circulate between it and the cover during exercise.

Experiments were conducted in a controlled temperature-humidity chamber with an air movement of approximately 0.3 m/s. For most experiments air temperature was closely controlled at about 27 $\pm$ .1^{o}C and relative humidity near 50%. A few experiments were run under other conditions; 27^{o}C and 20% r.h., and 34^{o}C with both 25% and 90% r.h., to provide a wider range for testing the prediction equations and the accuracy of estimate of some of the ensemble parameters, such as f_{cl} and w, which could not be measured.

During these experiments, the manikin was positioned on a servo-balanced platform scale which provided a printout at 30-second intervals. These data provided a record of water evaporation during the wet cover experiments; the average rate of loss, which was obtained using a least-squares fit on the data and converted to an equivalent evaporative heat loss rate, permitted a comparison with the evaporative heat loss rate (H_e) predicted by the mathematical model. A large pan was positioned between the manikin and scale to reduce the likelihood that drippings from the cover, in the event it was excessively wetted, would fall to the floor of the chamber and be recorded as an evaporative water loss.

Procedures used in operating the manikin were standard for this device. Heating was accomplished using a proportional-power temperature controller, coupled to a series of thermistor sensors in the manikin, which held average surface temperature during a given experiment constant within 0.1^{o}C at about 32^{o}C. With this close control it could be assumed that power input equaled manikin heat loss (H_{sk}). Power was continuously recorded during a run, utilizing a thermal wattmeter connected to a single pen strip chart recorder. Average manikin surface temperature ($\bar{T}_s$) was calculated by equally weighting recorded outputs from 21 copper-constantan thermocouples uniformly distributed, by area, over the copper shell. Air temperature (T_a) was also recorded at approximately 70-second intervals, using multiple paralleled thermocouples located at various heights around the manikin. Experiments lasted a minimum of 10 minutes, and were not commenced until after the manikin had been equilibrated. For the dry-skin runs, at least three hours was allowed for this equilibration.

For those runs where the "skin" on the manikin was wetted, the clothing items were either removed or opened sufficiently to allow the "skin" to be thoroughly wetted with a spray bottle. During the wetting, the manikin heaters remained energized so that average surface temperature was maintained near its control level. The clothing was then replaced and the system allowed to re-equilibrate for at least 30 minutes before recordings of power, temperature, etc., were made; i.e. until power level and the various temperatures had become practically constant. Similar rules were followed for wet cover runs. Water additions were made at intervals to maintain the cover wet; no experiment was begun until the system had completely restabilized.

Three, and sometimes four, experiments were run on a single day except where problems in obtaining a desired chamber environment delayed the equilibration process. Runs were made at approximately hourly intervals. Prior to each day's runs, the manikin was "redressed" by opening and dropping the ensemble and removing the gloves, then replacing the items, re-adjusting the cover, etc. This process was employed to prevent the layers from gradually settling against the manikin with time, and also to introduce variability in dressing as a factor in the study.

Additional thermocouples were attached to the inside of the impermeable layer and on the wettable cover surface, respectively, during the preliminary experiments which were conducted to establish the permeability index (i_m) of the clothing inside the vapor barrier, the skin-to-barrier insulating value (I_{si}), the barrier-to-cover surface insulation (I_{ic}), the combined intrinsic insulation (I_{cl}), and the total insulation including surface air layer (I_{tot}). Each of these insulating values was calculated in clo units using the general equation:

$$I_x = \frac{6.46\ A_{sk}\ (T_1 - T_2)}{H_{sk}}$$

where $(T_1 - T_2)$ was the applicable temperature gradient in ^{o}C; i.e., $(\bar{T}_s - T_i)$ for I_{si}, $(T_i - \bar{T}_{cl})$ for I_{ic}, $(\bar{T}_s - \bar{T}_{cl})$ for I_{cl}, and $(\bar{T}_s - T_a)$ for I_{tot}. During these insulation measurements, both the manikin "skin" and the cover were left dry.

The permeability index (i_m) for the layers beneath the impermeable vapor barrier was obtained by operating the manikin with its "skin" wet but with the cover dry. The applicable equation for calculating i_m was:

$$H_{sk} = \frac{6.46\ A_{sk}}{I_{si}} \left[(\bar{T}_s - T_i) + 2.2\ i_m\ (\bar{p}_s - p_i) \right]$$

where I_{si} is the insulating value from skin to vapor barrier, measured with the entire system dry, and the vapor pressures $\bar{p}_s$ and p_i are the saturated values at mean skin and impermeable barrier temperatures, respectively.

Similar procedures were used in the experiments for validating the mathematical model except that no thermocouples were used on the impermeable layer. However, measurements were made of the wettable cover temperature at four sites (viz: left breast, middle of the back, front of left thigh and right calf) to provide an average which could be compared with the value of $\bar{T}_{cl}$ calculated using the heat balance equation. These four thermocouples were sewn to the cover surface rather than being cemented or taped, to cause minimal effect on evaporation from the cover. Experiments were run with the manikin "skin" both dry and wet to provide as complete a check as possible on the model, even though in the practical situation the wearer's skin would be expected to be wet at any activity level in the heat with such an impermeable garment.

Results and Discussion

a. Ensemble parameters

Seven experiments at 27°C and 50% relative humidity with the manikin "skin" and ensemble cover dry gave an average value for intrinsic insulation (I_{cl}) of 0.294°C m²/W (1.90 clo) and a total insulation value, including the surface air layer, of 0.381°C m²/W (2.46 clo). The difference (0.087°C m²/W or 0.56 clo) represents the insulation of the surface air layer, which is equal to I_a/f_{cl}. The indicated value of f_{cl} is 1.32 based on an I_a value of 0.75, obtained using h_r = 4.60 W/m² °C and h_c = 4.03 W/m² °C, the value at the chamber air movement, 0.3 m/s, using Mitchell's relationship (Equation 8); i.e., $I_a = 6.46/(h_r + h_c)$ which yields 0.75 clo. This value agrees within 3% with that measured on the nude manikin. A similar value for f_{cl} (f_{cl} = 1.29) is obtained using an expression proposed by Gagge from Fanger's data (7) ($f_{cl} = 1 + 0.15\, I_{cl}$, where I_{cl} is in clo units). Accordingly, f_{cl} has been assigned a value of 1.3 for all calculations in this study.

Values of other parameters for the ensemble were obtained from separate experiments under similar environmental conditions with the manikin controlled to produce a mean skin temperature $\bar{T}_s$ of about 33°C. Indicated values obtained by temperature measurements within the clothing were:

I_{si} (skin to impermeable layer insulation) = 1.20 clo

I_{ic} (impermeable layer to clothing surface insulation) = 0.70 clo

i_m (permeability index of layers beneath impermeable barrier) = 0.43

b. Model validation experiments

The experimental data for the wet-cover runs, the predicted values of the parameters of Equation 5, and a comparison of predicted and measured clothing surface temperatures ($\bar{T}_{cl}$), cover evaporative cooling loss (H_e), and skin heat loss (H_{sk}), are given in Tables I through III, respectively. The net cooling benefits at the body surface which occur as a result of the evaporative heat loss at the outer cover are also included in Table II.

Of the 15 runs which were made, only the last three tabulated were conducted with the manikin "skin" wet. The dry-skin runs are basically grouped according to air relative humidity, because of its importance in determining water evaporation from the cover. Runs 1 through 4 were made on a single day without changing environmental conditions. Runs 5 through 7 were also made in one day. These runs, plus run 8 on another day, were all made under similar conditions, 26 to 27° air temperature with about 50% relative humidity. Runs 9 and 10, on separate days, were low humidity runs (run 9 was made at 26°C, and run 10 with air temperature practically equal to manikin mean skin temperature); run 11 and 12 were high humidity experiments with air temperatures as in runs 9 and 10 respectively. These combinations were selected to provide as wide an environmental range as possible for the model validation.

The three wet "skin" runs were all made on a single day, but each can be considered a separate experiment since removal or opening of the clothing to wet the "skin" between runs constituted a redressing, or rearrangement of clothing on the manikin. This process introduced dressing variables such as drape, spacing between layers, etc., and permitted assessment of their effect on wet cover cooling benefits despite the limited number of wet "skin" runs. On the other hand, a similar assessment based on the dry "skin" runs requires comparison of all the runs made on at least two days, since the dress was altered once a day.

Since the conditions for runs 1 to 8 were similar, the model predictions in Table II for $\bar{T}_{cl}$ or any of the heat balance components show little variability. The experimental results (Table III) are more varied, but the agreement between predicted and measured values are generally quite satisfactory. In the first series, runs 1 through 4, the predicted cover evaporative losses differed from those derived from scale weighings by a maximum of 12 W, compared to 10 W in the second series (runs 5 through 7) and 21 W in run 8. These discrepancies are due mainly to uncertainty in estimating the rate of water evaporation from the cover. Although the scale weighings were reliable, the rate of weight loss did not necessarily provide an accurate indication of water loss from the wetted cover. No precautions were taken to prevent evaporation of water which dripped into the pan under the manikin. Consequently, the measured rates of water loss may be slightly high, which would explain why the evaporative cooling loss rates based on the weighings were usually higher than predicted values of H_e. The differences in some of the later runs might appear to dispute this reasoning; however, it must be realized that cover evaporation at low humidity (runs 9 and 10) would be rapid, which would tend to reduce the likelihood of dripping, while at high humidity (runs 11 and 12) any excess wetting of the cover would, because of slow evaporation, cause considerable drainage into the pan. It is conceivable that this drainage increased the actual area for evaporation enough to account for most of the difference in a given run.

The differences between measured and predicted skin heat losses for runs 1 to 8 are small, and indicate that the model is valid for a non-sweating inactive man. As was anticipated, a day-to-day variation in skin cooling is introduced by dressing factors; this variation is not handled by the model but does not appear to be large. The differences between predicted and measured losses are 1 W or less in series 1 (runs 1–4), compared with a 5 W maximum in series 2 (run 5–7), and 2 W in run 8.

Agreement of the model predictions with measured heat losses is not quite as satisfactory for the low humidity runs (runs 9 and 10), where the differences were 7.2 and 9.6 W, respectively. These discrepancies are understandable, however, in view of the rapid cover evaporation and high values of H_e which resulted from the low air vapor pressures and large clothing surface-to-air vapor pressure gradients. In these runs, the gradients based on predicted $\bar{T}_{cl}$ were 12.4 and 14.1 mm Hg, compared with gradients of less than 8 mm Hg in runs 1-8. These increases in H_e also caused surface temperature to drop below air temperature (i.e., make $(T_a - \bar{T}_{cl})$ large) which sharply raised $(H_r + H_c)$ values (Table II). Accordingly, $(H_r + H_c)$ and H_e, and their defining factors h_c, h_r, f_{cl} and w, became critical in defining $\bar{T}_{cl}$, on which the accuracy of predicting H_{sk} depends. The predictions might be improved if the defining factors were known with more precision, but it must also be remembered that $\bar{T}_{cl}$ does not correctly represent a true mean cover temperature, especially when its temperature is greatly depressed by rapid evaporation. From the earlier discussion of this deficiency in the model, it should be evident that prediction accuracy will decrease as the difference between $\bar{T}_{cl}$ and T_c becomes larger. This will occur when evaporative cooling, and the difference in temperature between the wetted and unwetted surfaces on the ensemble, increases.

In runs 11 and 12, where air relative humidities were 89 and 90% respectively, the evaporative losses were small and $\bar{T}_{cl}$ was only slightly depressed below air temperature. Both $(H_r + H_c)$ and H_e were therefore of less importance, relative to H_{sk}, in determining $\bar{T}_{cl}$. As a result, the accuracy of the model predictions is improved, and the predicted H_{sk} values agree closely with measured heat losses. The poor agreement between the measured and predicted cover evaporative losses has already been noted. However, one must conclude that the predicted values are more nearly correct, judging from the predicted vs measured H_{sk} comparisons. If the measured evaporative losses had been used in the heat balance, discrepancies in predicting H_{sk} of 16 and 29 W would have been obtained. It is acknowledged that the potential for error in predicting $\bar{T}_{cl}$ and H_e in these runs is high owing to the small $(T_a - \bar{T}_{cl})$ and $(p_a - p_{cl})$ gradients involved; i.e., 0.07°C and -2.77 mm for run 11, and 1.00°C and -1.68 mm for run 12. If the predicted $\bar{T}_{cl}$ in run 11 were raised 0.2°C to 26.7°C $(H_r + H_c)$ would change from + 1.25 to -3.55 W and H_e from -35.50 to -53.68 W. H_e would then be about 30% closer to the measured value. However, the predicted H_{sk} would change to 57.2 W, or 8.6 W higher than the measured value.

Table III indicates close agreement between the predicted and measured H_{sk} values for the wet "skin" experiments, runs 13 to 15 inclusive. This agreement may be fortuitous since only a limited number of measurements were taken to evaluate I_{si} and I_{ic}, and i_m of the fatigues under the impermeable layer. From temperature data collected on the dry system, i.e., with both the manikin "skin" and wettable cover dry, the ratio I_{si}/I_{ic} was determined from the equation

$$\frac{I_{si}}{I_{ic}} = \frac{T_s - T_i}{T_i - T_{cl}}$$

where T_s, T_i, and T_{cl} were <u>local</u> skin, impermeable layer, and clothing surface temperatures measured over a given manikin skin site, i.e., with all three thermocouples over the same segment of the copper surface. The ratio I_{si}/I_{ic} determined by averaging values for four segments (on the back, chest, stomach, and thigh) was 1.8: I_{si} and I_{ic} were accordingly 1.2 and 0.7 clo, respectively (since the ensemble intrinsic insulation I_{cl} was equal to 1.9 clo). The permeability index i_m for the fatigues, calculated from data obtained in wet "skin", dry cover runs and using 1.2 clo for I_{si}, was 0.43. These values of insulation and i_m for the fatigues seem reasonable based on the values for fatigues alone, namely, a total insulation including surface air layer, of 1.37 clo and an i_m of 0.43. In the ensemble, the impermeable layer overlying the fatigues would reduce the insulation of their surface air layer to some extent, but probably by no more than 30%, or 0.2 clo, since the impermeable layer was rather stiff and loose fitting. The i_m value for the fatigues would not be expected to change when the impermeable layer was added. Unfortunately, the predicted H_{sk} is rather sensitive to the value of I_{si} chosen. Using a value of 1.37 clo for I_{si}, and a corresponding value for i_m of 0.51 (higher than normally measured at low air movement), results in a prediction for H_{sk} of 110 W for run 13, or 11.4 W higher than when I_{si} of 1.20 clo was used. Any inaccuracy in measuring T_s, T_i or T_{cl} when determining I_{si}/I_{ic} obviously has an important effect on the predicted skin heat loss (H_{sk}). Nevertheless, the generally close agreement between the predicted and measured skin heat losses in runs 13 to 15, Table III indicates that the various heat exchanges with a wet skin are correctly handled in the model, and that realistic predictions of skin cooling can be made if the ensemble parameters are correct.

In most runs, the predicted $\bar{T}_{cl}$ values in Table II are lower than the measured values in Table I. The differences are lower (-0.3 to + 2.0°C) for the 50 and 90% relative humidity dry skin runs than for the low humidity runs (2.7 to 3.0°C) and the wet "skin" runs (1.9 to 2.1°C). These differences are largely due to the usual errors in measuring clothing surface temperature, i.e., the thermocouples were partially exposed to the air layer rather than to the clothing surface alone; this surface was in most cases below air temperature and the thermocouples accordingly read too high. The errors seem to correlate well with net heat loss from the surface (i.e. with (H_r + H_c + H_e)) although there is one instances (run 12) where a measured surface average slightly below predicted $\bar{T}_{cl}$ was obtained. No explanation for this contradictions is apparent.

Cooling Benefits from Cover Evaporation Losses. The predicted increases in skin heat loss caused by evaporation from the cover are given in the last column of Table II. Each value was obtained by subtracting the calculated manikin heat loss (H_{sk}) with a dry cover from that with wet cover. For the dry-skin runs, these results may also be obtained by multiplying the predicted H_e values by Burton's efficiency factor, in Equation 1, i.e.,:

$$\text{Cooling Benefit} = H_e \left(\frac{I_a}{f_{cl}\ I_{tot}}\right)$$

For I_a equal to 0.75 clo at 0.3 m/s air movement (from Equation 9) and I_{tot} equal to 2.46 clo, the cooling efficiency $I_a/(f_{cl}\ I_{tot})$ is 0.234 or 23.4%.

Burton's equation is not applicable to the wet "skin" runs because, even with the vapor barrier, there is evaporative heat transfer from the skin to the impermeable layer. This evaporative transfer in effect reduces the thermal insulation of the inner layers and, by extension, the effective value of I_{tot}. Cooling efficiency and the benefits of cover evaporation are, therefore, increased.

In runs 13 to 15, the average efficiency, i.e., the benefit divided by H_e, is 33.9% or a 45% increase over the dry skin value. The true wet "skin" efficiency, unlike that for dry skin, is not constant since (p_s - p_i) is not a linear function of the temperature gradient $\bar{T}_s$ - T_i (it will appear constant using the model, however, because a linear relationship, Equation 16, has been assumed). As ($\bar{T}_s$ - T_i) increases, sensible heat transfer from the skin to impermeable layer changes linearly but (p_s - p_i) and the evaporative transfer increase by a larger percentage, thus lowering the effective insulation between the skin and impermeable layer. Highest cooling efficiencies may therefore be expected when the $\bar{T}_s$ - T_i gradient is large, as in cool environments or where the cover temperature is greatly depressed below ambient by rapid evaporation.

Table III indicates a secondary effect of the internal evaporation cycle which produces even greater cooling benefits than the increased efficiency would indicate. The environments and manikin $\bar{T}_s$ in runs 13 to 15 are comparable to those in dry-skin runs 1 through 4, but the cooling benefits in the former runs are 64% greater, rather than the 45% increase based on cooling efficiency. Because of the reduced effective insulation in the wet "skin" runs, $\bar{T}_{cl}$ is about 0.8°C higher than in the dry "skin" runs, causing a change in ($H_r + H_c$) of about 16 W and a similar increase in cover evaporative loss (H_e). The net result, after adjusting for the increased dry cover H_{sk}, is a cooling benefit about 20 W higher than in the dry "skin" runs, or 6 W more (33.9% of the increase in H_e) than would be predicted on the basis of efficiency factor alone.

Model Predictions

Predicted values of supplementary cooling, and of the minimal water requirements to maintain the cover wet, for a 1.8 m^2 man wearing the experimental ensemble in various combinations of air temperature, relative humidity and wind speed are given in Figure 1 and Tables IV and V. Values of skin net heat dissipation with wet cover are given in Table VI. These predictions are based on the 0.3 m/s values for I_{si}, I_{ic} and permeability index i_m obtained in the chamber experiments, and do not include any effects of solar radiation. A mean skin temperature ($\bar{T}_s$) of 37°C, which would be typical for a stressed man in an impermeable ensemble, has been assumed in making the predictions.

Figure 1 suggests the effects of wind for environments of 30°C at 50% and 70% r.h., and 45°C at 20% and 30% r.h., which represent typical tropical and hot-dry conditions, respectively; curves are also included for 30°C, 30% humidity to show, separately, the importance of air temperature and of relative humidity in setting the supplementary cooling levels and water requirements. In general, cooling increases most rapidly with wind at low air movement and tends to plateau at wind speeds above 3 m/s; this simply reflects the fact that h_c increases most rapidly at lower wind speeds and becomes nearly constant at winds above 5 m/s. At 20% and 30% relative humidities, cooling continues to increase above 3 m/s, but at 30°C and 70% humidity it reaches a maximum at 3 m/s, and declines slightly above that speed. Water requirements, on the other hand, increase steadily with wind and show little tendency to level off at high winds. These requirements are higher and rise most rapidly with wind when air humidity is low. By comparing the cooling benefits and water requirements, it is evident that the cooling efficiency of the water evaporated from the cover falls off as wind speed increases; this reduced efficiency is predicted by Equation 1, Burton's equation, since I_a falls rapidly with wind while total insulation decreases more slowly inasmuch as it has been assumed that $I_{si} + I_{ic}$, the intrinsic insulation of the clothing, is unaffected by wind. As already noted, Burton's equation is merely indicative of the efficiency trend if the inner clothing layers are wet; however, the internal evaporative heat transfer is reasonably unaffected by wind (assuming i_m constant) and the fact that efficiency will decrease with wind can therefore be inferred from Equation 1.

In Figure 1, a 15°C change in air temperature has about the same effect as a 20% change in relative humidity; the curve intervals from 30°C to 45°C with constant 30% humidity are approximately the same as those for a humidity change from 30% to 50%, or 50% to 70%, at a constant 30°C temperature. This particular comparison applies only to the environments of Figure 1; different relationships are found in Tables IV and V. For example, at 5 m/s and 70% r.h., a change from 25°C to 40°C increases supplementary cooling only 1 watt, versus 12 to 19 watts for a 10% increase/decrease in relative humidity (70% to 80% or 70% to 60%); at low humidities, a 5°C change sometimes has more effect than a 10% humidity change. Thus, no general rule for relating temperature and humidity effects can be formulated.

Tables IV and V provide predictions of supplementary cooling and water requirements, respectively, for air temperatures from 25°C to 50°C, (in 5°C increments) over the humidity range from 10% to 100% (in 10% increments); values for abnormally high dew points have been omitted since these environments seldom occur in nature. Predictions are made only for wind speeds of 0.5, 1, and 5 m/s, but values at intermediate wind speeds may be obtained with sufficient precision by simple linear interpolation, particularly between 1 and 5 m/s. The information in these tables was produced by a computer solution of Equation 19 for $\bar{T}_{cl}$, using the Keenan-Keyes equation (14) for determining saturated vapor pressure $\bar{p}_{cl}$ rather than the approximation given by Equation 12.

The results in these tables show that, for the most frequently encountered environments, supplementary cooling of important magnitude can be provided with reasonable water supply cost. For example, at the cooler temperatures 25°C and 30°C, and 60% relative humidity (dew points of about 17°C and 21°C), the wet cover provides increased cooling of from 53 to 62 W, with water evaporation of 0.26 to 0.67 kg/hr. In a typical hot dry environment of 50°C, 20% humidity (dew point 20°C), where supplementary cooling is most essential since, without the wet cover, the body would not only be producing heat by metabolism but also gaining heat rapidly from the environment by sensible heat transfer through the clothing, the cooling benefits increase to from 135 to183 W, at a water cost which ranges from 0.66 to 1.91 kg/hr.

Since the supplementary cooling data in Table IV provide no insight into the net skin heat loss with wet cover, these values are presented in Table VI. Data in this table serve two purposes: (1) furnish information on which to assess the degree of balance between a man's heat production and his heat loss, and (2) permit calculation of the skin heat loss with dry cover, by subtraction of the appropriate supplementary cooling values in Table IV. The results show clearly that, with this particular ensemble, heat dissipation is generally not adequate to maintain thermal balance during extended periods of moderate to heavy activity (required dissipation of 300 to 400 W). On the other hand, the benefits from the wet cover in terms of extended tolerance time in hotter environments are almost self-evident. In a 35°C, 50% environment with 1 m/s wind, the heat dissipation without the cover wetted is predicted as 20 W (92–72) which, for a work level requiring 300 W dissipation for thermal balance, leaves a heat storage rate of 280 W. On the other hand, the storage rate with a wet cover would be 208 W (300–92) or 74% of the dry cover rate. Since the man's tolerable heat storage before collapse does not very greatly (15), one may conclude that the wet cover extends tolerance time, after $\bar{T}_s$ reaches 37°C, by 35% (1/0.74). Moreover, the man in a dry-cover ensemble would elevate his skin and body temperature more rapidly and reach 37°C $\bar{T}_s$ before the individual with a wetted cover. Thus, the wet cover could easily mean the difference between completing and not completing a given mission.

The predicted cooling benefits of a wet cover are minimal values for the ensemble which will be exceeded during body motion; the model assumes constant insulating values (clo) and permeability indices (i_m), based on the static, copper man measurements, but the increased air movements, or "pumping" associated with body motion will reduce I_{si} and I_{ic}, and increase i_m, by setting up convection currents within the ensemble. Such a change in one or all of these parameters would increase the cooling efficiency of the evaporation from the cover, and therefore the rate of supplementary cooling. Calculations simply assuming a decrease in I_{si} from 1.2 clo to 0.8 clo, a very reasonable reduction for the effect of body motion, show that, at 30°C and 50% humidity, supplementary cooling for the 1 to 5 m/s range increases by 10 to 11 W, producing a net skin dissipation increase of from 17 to 20 W; the latter is higher since dry cover dissipation is increased by reducing the ensemble insulation. At 45°C, 20% humidity with the same I_{si} reduction, supplementary cooling increases by 17 to 22 W, but the net cooling only increases by 12 to 16 W (less because the dry-cover heat gain at the skin is higher). Additional benefits would accrue from an increase in i_m. Further work is obviously required to define the effects of wind on the three parameters and to describe the changes with "pumping" during body motion, in terms of an effective wind velocity (V_{eff}), by conducting physiological studies on human subjects (10); these determinations have been made for four standard military ensembles, but not for an impermeable-type system.

Thus far, the predictions have not included any effects of solar radiation absorbed at the surface of the ensemble. This source of heating is handled by the term H_s in the heat balance, Equation 5. H_s is independent of $\bar{T}_{cl}$ and changes all the other factors in Equation 5, namely, $(H_r + H_c)$, H_e, and H_{sk}. The effect on H_e plays an important role in reducing the additional heat load at the skin surface due to solar radiation, commonly called the solar heat load, which will be discussed later.

To illustrate effects of solar radiation, predictions of supplementary cooling benefits, etc. have been made at wind velocities of 1 to 5 m/s (in 1 m/s increments) for two environments, 30°C with 50% r.h., and 45°C, 20% r.h.; the results are presented in Tables VII and VIII, respectively, along with values calculated for no solar radiation. In making these predictions, it has been assumed that a total of 300 W of solar radiation, from direct, diffuse, and terrain-reflected sunlight, is absorbed at the clothing surface. This total was obtained using our solar heat load model equations (2), assuming typical clear sky values of direct and diffuse radiation, a 60° solar angle, and a standing 1.8 m^2 man dressed in the experimental ensemble. Direct transmission of solar radiation has been assumed not to occur. No effects of "pumping" are considered in defining the ensemble parameters, i.e., the static values given initially for I_{si}, I_{ic}, and i_m were employed in making the predictions.

The predictions show that the solar heat load with a dry cover both decreases with wind and is independent of air temperature and humidity. Effectiveness of absorbed sunlight in modifying skin heat dissipation is given simply by Equation 1, with I_{tot} adjusted to account for the skin-to-impermeable cover (i.e. internal) evaporative heat transfer. This efficiency factor decreases with increasing wind, (since I_a is reduced) and depends on clothing parameters but not on air temperature or humidity. Moreover, the predictions show that the dry cover solar radiation heating efficiencies (H_s heating efficiency, dry) and the wet cover cooling efficiencies are identical (e.g., 0.25 at 1 m/s), which is logical since Equation 1 applies equally well for the addition of heat or its removal at the clothing surface.

In both Tables VII and VIII, it is observed that, at a given wind speed, supplementary cooling with a wet cover is higher with sunlight, by from 27 to 47 W depending on the wind speed and, to a slight extent, on the environment. This increase in cooling, which occurs because sunlight raises the clothing surface temperature $\bar{T}_{cl}$ and causes increased evaporation (cf water requirements with and without sunlight), has important implications since it reduces the heat stress associated with solar load. For example, in Table VII (30°C, 50% r.h.) the solar heat load with wet cover is only 33 W at 1 m/s instead of 76 W with the cover dry; the apparent efficiency of the absorbed sunlight is only 11% instead of the dry cover value of 25%. At 5 m/s, the solar heat load is reduced from 42 to 15 W, and the efficiency of solar heating from 14% to 5%. The reductions at comparable winds for 45°C, 20% r.h. (Table VIII) are greater than at 30°C, 50% r.h., but not dramatically so. These effects of a wet cover in reducing heat stress on the man are not obtained without cost, namely, an increase in water requirements. At 1 m/s, 0.25 kg/hr more water is needed at 30°C, 50% r.h., and 0.28 kg/hr more at 45°C, 20% r.h.; at 5 m/s, the increased water requirements are 0.28 kg/hr and 0.30 kg/hr, respectively. These increases are not prohibitive, but do complicate the water supply problem to some extent (36 to 60% more water at 30°C, 50% r.h., and 17 to 33% more at 45°C, 20% r.h.).

The maximal indicated water requirement of about 2 kg/hr is about half the amount which can be held in a standard U.S. Army helmet and about two thirds that which can be held by a helmet liner. If careful wetting of the cover is performed, this amount of water can be applied without dripping. Of course, if the water is simply poured over the head, even a full helmet of water may not prove sufficient to completely wet the cover, and large amounts of water will drip or be splashed onto the ground. It is clear that some method of uniformly applying water, such as a hand pump spray system, will produce more satisfactory results without wasting water. The amount of water applied should probably be titrated (e.g. 10 pumps) so that enough water to last at least one hour will be applied at each wetting.

In concluding this discussion of the benefits of a wet cover over an impermeable clothing system, it is emphasized that the predictions which have been made are necessarily approximations because of uncertainties in some of the factors in the prediction equations. Those associated with wind and body motion have been discussed. Others which have not been exactly defined are the vapor pressure-temperature relationship at the impermeable layer and the radiant heat transfer coefficient h_r, which has been assumed constant. The latter may be adjusted in accordance with the average of clothing surface and air temperatures using the data in Table IX as a guide. In arriving at a suitable value for h_r, the values of R in this table should be multiplied by the factor 0.7 to account for first, the non-blackbody characteristics of the clothing surface (emissivity about 0.9 instead of unity) and second, reduction of effective radiating area due to the shape of the human body. For a clothed man, this area is reduced to about 80% of clothing surface area (assuming similar reductions for nude and clothed man) because of adjacent or facing areas which merely exchange radiation with each other but not with the environment; the main areas involved are the inner surface of the legs, and the adjacent areas of the arms and torso.

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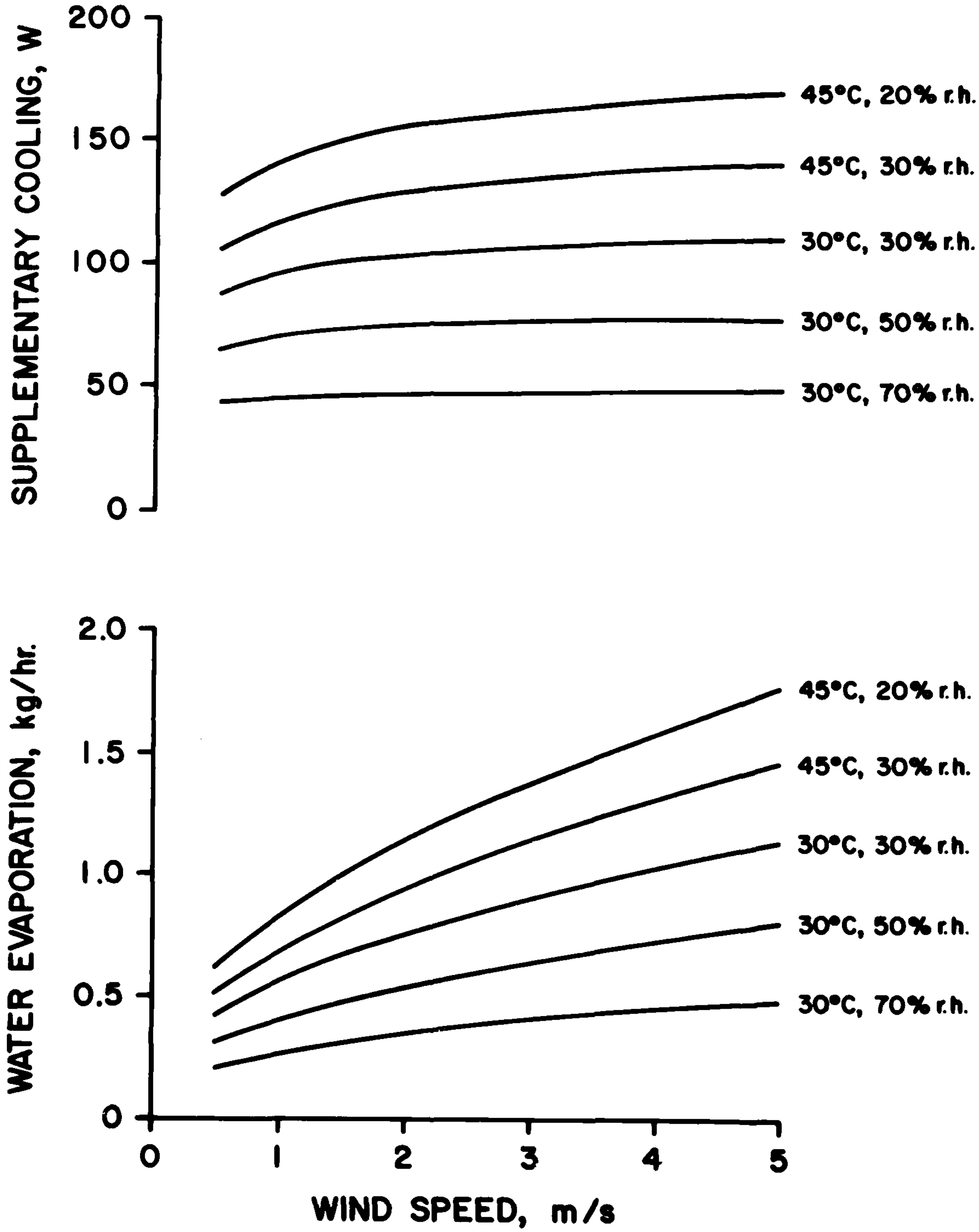

Figure 1: Predictions of supplementary cooling and water requirements with wetted cover for five temperature-humidity combinations.

Table I

Experimental Data with Wetted Cover

Run No.	$\bar{T}_s$	T_a	r.h.	Manikin Loss	Water Loss	Measured $\bar{T}_{cl}$
Dry Skin	(^oC)	(^oC)	(%)	(W)	(kg/hr)	(^oC)
1	33.56	26.57	51.4	66.53	.217	24.4
2	33.61	26.58	51.4	66.02	.206	25.0
3	33.67	26.61	51.3	65.03	.211	25.2
4	33.64	26.60	51.4	66.26	.221	24.9
5	32.59	26.27	52.0	56.54	.202	23.5
6	32.62	26.21	51.9	58.10	.211	23.5
7	32.61	26.21	51.9	58.14	.193	23.4
8	32.78	26.28	52.1	60.37	.228	23.4
9	33.40	25.95	19.8	78.59	.334	22.6
10	34.26	34.36	25.0	46.14	.385	28.4
11	33.71	26.53	89.0	48.60	.098	26.8
12	34.76	34.52	90.5	9.73	.090	33.2
Wet Skin						
13	33.28	26.61	51.7	99.5	.258	25.9
14	33.28	26.61	51.3	99.5	.279	26.1
15	33.33	26.61	51.0	99.0	.223	26.1

Table II

Predicted Results and Cooling Benefits

with Wetted Cover

Run No.	$\bar{T}_{cl}$	(H_r+H_c)	H_e	H_{sk}	Dry Cover H_{sk}	Cooling Benefit
Dry Skin	(^oC)	(W)	(W)	(W)	(W)	(W)
1	23.20	70.32	-135.87	65.55	33.92	31.63
2	23.22	70.11	-136.17	66.06	34.12	31.94
3	23.24	70.43	-136.34	65.91	34.26	31.65
4	23.24	70.22	-136.09	65.87	34.17	31.70
5	22.92	69.91	-131.21	61.30	30.67	30.63
6	22.87	69.70	-131.54	61.84	31.11	30.73
7	22.87	69.70	-131.54	61.84	31.06	30.78
8	22.94	69.70	-132.06	62.36	31.55	30.81
9	19.86	127.08	-212.84	85.76	36.16	49.60
10	25.40	186.97	-242.68	55.71	-0.49	56.20
11	26.47	1.25	- 47.50	46.26	34.85	11.41
12	33.52	20.87	- 28.81	7.94	1.16	6.78
Wet Skin						
13	24.02	54.05	-152.64	98.59	46.95	51.64
14	24.00	54.46	-153.79	99.33	46.95	52.38
15	23.98	54.88	-154.70	99.82	47.37	52.45

Table III

Comparison of Measured and Predicted Values

Run No.	Clothing Surface Temperature (°C)			Cover Evaporative Cooling (W)			Skin Heat Loss (W)		
Dry Skin	Meas.	Pred.	Diff.	Meas.	Pred.	Diff.	Meas.	Pred.	Diff.
1	24.4	23.2	1.2	146	136	10	66.5	65.5	1.0
2	25.0	23.2	1.8	138	136	2	66.0	66.1	-0.1
3	25.2	23.2	2.0	142	136	6	65.0	65.9	-0.9
4	24.9	23.2	1.7	148	136	12	66.3	65.9	0.4
5	23.5	22.9	0.6	135	131	4	56.5	61.3	-4.8
6	23.5	22.9	0.6	142	132	10	58.1	61.8	-3.7
7	23.4	22.9	0.5	129	132	-3	58.1	61.8	-3.7
8	23.4	22.9	0.5	153	132	21	60.4	62.4	-2.0
9	22.6	19.9	2.7	224	213	11	78.6	85.8	-7.2
10	28.4	25.4	3.0	258	243	15	46.1	55.7	-9.6
11	26.8	26.5	0.3	66	47	19	48.6	46.3	2.3
12	33.2	33.5	-0.3	60	29	31	9.7	7.9	1.8
Wet Skin									
13	25.9	24.0	1.9	173	153	20	99.5	98.6	0.9
14	26.1	24.0	2.1	187	154	20	99.5	99.3	0.2
15	26.1	24.0	2.1	150	155	-5	99.0	99.8	-0.8

Table IV

Supplementary Cooling with Wet Cover (W)

(No Sunlight)

Rel. Temp/Hum. °C	10%	20%	30%	40%	50%	60%	70%	80%	90%	100%
				Wind Speed 0.5 m/s						
25	99	89	80	71	62	53	44	36	28	20
30	111	99	87	76	64	54	43	33	23	13
35	123	108	94	80	66	53	40	28	16	5
40	136	117	100	83	66	51	36	22		
45	149	126	105	85	66	47				
50	162	135	109	86						
				Wind Speed 1.0 m/s						
25	110	99	88	77	67	56	46	37	27	18
30	124	110	96	83	70	58	46	34	23	12
35	138	121	104	88	72	58	44	30	17	4
40	153	132	111	92	74	56	40	24		
45	168	142	118	95	74	54				
50	183	152	123	97						
				Wind Speed 5.0 m/s						
25	128	113	98	84	71	58	46	34	23	12
30	146	127	109	93	77	62	47	34	20	8
35	164	141	120	100	82	64	48	32	17	3
40	183	156	130	107	86	66	47	29		
45	202	169	140	114	89	67				
50	221	183	149	119						

Table V

Water Requirements to Maintain Cover Wet (kg/hr)

(No Sunlight)

Temp/Rel. Hum. °C	10%	20%	30%	40%	50%	60%	70%	80%	90%	100%
					Wind Speed 0.5 m/s					
25	0.48	0.44	0.39	0.35	0.30	0.26	0.22	0.18	0.14	0.10
30	0.54	0.48	0.43	0.37	0.32	0.26	0.21	0.16	0.11	0.06
35	0.60	0.53	0.46	0.39	0.32	0.26	0.20	0.14	0.08	0.02
40	0.67	0.58	0.49	0.41	0.33	0.25	0.18	0.11		
45	0.73	0.62	0.51	0.42	0.32	0.23				
50	0.79	0.66	0.54	0.42						
					Wind Speed 1.0 m/s					
25	0.64	0.58	0.51	0.45	0.39	0.33	0.27	0.22	0.16	0.11
30	0.73	0.64	0.56	0.49	0.41	0.34	0.27	0.20	0.13	0.07
35	0.81	0.71	0.61	0.51	0.42	0.34	0.26	0.18	0.10	0.02
40	0.90	0.77	0.65	0.54	0.43	0.33	0.24	0.14		
45	0.98	0.83	0.69	0.56	0.43	0.32				
50	1.07	0.89	0.72	0.57						
					Wind Speed 5.0 m/s					
25	1.33	1.18	1.03	0.88	0.74	0.61	0.48	0.36	0.24	0.12
30	1.52	1.32	1.14	0.97	0.80	0.64	0.49	0.35	0.21	0.08
35	1.71	1.47	1.25	1.05	0.85	0.67	0.50	0.33	0.18	0.03
40	1.90	1.62	1.36	1.12	0.90	0.69	0.49	0.31		
45	2.10	1.77	1.46	1.18	0.93	0.69				
50	2.30	1.91	1.56	1.24						

Table VI

Net Skin Heat Dissipation with Wet Cover (W)

(No Sunlight)

Temp/Rel. Hum. °C	10%	20%	30%	40%	50%	60%	70%	80%	90%	100%
				Wind Speed 0.5 m/s						
25	189	179	170	161	152	143	134	126	118	110
30	165	153	141	130	118	108	97	87	77	67
35	141	126	112	98	84	71	58	46	34	23
40	118	100	82	65	49	33	18	4		
45	95	73	51	31	12	-6				
50	72	45	20	-4						
				Wind Speed 1,0 m/s						
25	206	195	184	173	163	153	143	133	124	115
30	182	168	154	141	128	116	104	92	81	70
35	158	140	123	107	92	77	63	49	36	24
40	134	112	92	73	55	37	21	5		
45	110	84	60	38	16	-3				
50	87	56	27	1						
				Wind Speed 5.0 m/s						
25	238	224	209	195	182	169	157	145	134	123
30	212	194	176	159	143	128	114	100	87	74
35	164	141	143	123	104	87	70	54	39	25
40	161	134	109	85	64	44	25	8		
45	136	103	74	47	23	1				
50	111	73	39	9						

Table VII

Effect of Absorbed Sunlight with Wet Cover
$30^{o}C$, 50% RH Environment

V(m/s)	1	2	3	4	5
No Sunlight					
H_{sk}, dry cover (W)	58	62	64	66	66
H_{sk}, wet cover (W)	128	136	139	142	143
Cooling supplement (W)	70	74	75	76	77
H_e at wet cover (W)	275	362	429	486	537
Cooling efficiency (%)	0.25	0.20	0.18	0.16	0.14
Water requirement (kg/hr)	1.11	1.42	1.67	1.88	2.07
Absorbed sunlight H_s = 300 W					
H_{sk}, dry cover (W)	-18	0	11	18	24
H_{sk}, wet cover (W)	95	111	119	124	128
Cooling supplement (W)	113	111	108	106	104
H_e at wet cover (W)	445	541	613	673	726
Cooling efficiency (%)	0.25	0.20	0.18	0.16	0.14
Water requirement (kg/hr)	0.66	0.81	0.92	1.00	1.08
Analysis					
Solar load, dry cover (W) (dry cover H_{sk} diff.)	76	62	53	48	42
H_s heating efficiency, dry (%) (dry cover H_{sk} diff. ÷ 300)	0.25	0.20	0.18	0.16	0.14
Solar load, wet cover (W) (wet cover H_{sk} diff.)	33	25	20	18	15
H_{sk} heating efficiency, wet (%) (wet cover H_{sk} diff. ÷ 300)	0.11	0.08	0.07	0.06	0.05

Table VIII

Effect of Absorbed Sunlight with Wet Cover
45°C, 20% RH Environment

V(m/s)	1	2	3	4	5
No Sunlight					
H_{sk}, dry cover (W)	-58	-61	-63	-65	-66
H_{sk}, wet cover (W)	84	94	99	101	103
Cooling supplement (W)	142	155	162	166	169
H_e at wet cover (W)	557	760	921	1059	1184
Cooling efficiency (%)	0.25	0.20	0.18	0.16	0.14
Water requirement (kg/hr)	0.83	1.14	1.37	1.58	1.77
Absorbed sunlight H_s = 300 W					
H_{sk}, dry cover (W)	-134	-123	-116	-112	-109
H_{sk}, wet cover (W)	55	72	81	86	89
Cooling supplement (W)	189	195	197	198	198
H_e at wet cover (W)	741	954	1119	1260	1386
Cooling efficiency (%)	0.25	0.20	0.18	0.16	0.14
Water requirement (kg/hr)	1.11	1.42	1.67	1.88	2.07
Analysis					
Solar load, dry cover (W) (dry cover H_{sk} diff.)	76	62	53	47	43
H_s heating efficiency, dry (%) (dry cover H_{sk} diff. ÷ 300)	0.25	0.20	0.18	0.16	0.14
Solar load, wet cover (%) (wet cover H_{sk} diff.)	29	22	18	15	14
H_s heating efficiency, wet (%) (wet cover H_{sk} diff ÷ 300)	0.10	0.07	0.06	0.05	0.05

Table IX

Values of the radiation exchange coefficient R in ($W/m^2\ {}^oC$)

for temperatures from 20^oC to 50^oC

According to the equation:

$$R(t_1 - t_2) = \sigma(T_1^4 - T_1^4)$$

where t_1, t_2 are surface and air temperatures, ^oC

T_1, T_2 are surface and air temperatures, ^oK

σ is Stefan constant, $5.67 \times 10^{-8}\ W/m^2\ {}^oK^4$

Note: Values are for blackbody radiation, 100% exposed surface. Select R at the mean of t_1 and t_2, i.e., at $\bar{t} = \frac{t_1 + t_2}{2}$

$\bar{t}$	R	$\bar{t}$	R	$\bar{t}$	R	$\bar{t}$	R
20	5.72	30	6.32	40	6.97	50	7.66
21	5.78	31	6.39	41	7.04	51	7.73
22	5.83	32	6.45	42	7.10	52	7.80
23	5.89	33	6.51	43	7.17	53	7.87
24	5.95	34	6.58	44	7.24	54	7.95
25	6.01	35	6.64	45	7.31	55	8.02
26	6.08	36	6.71	46	7.38	56	8.09
27	6.14	37	6.77	47	7.45	57	8.17
28	6.20	38	6.84	48	7.52	58	8.24
29	6.26	39	6.90	49	7.59	50	8.32