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TECHNICAL REPORT
EP-30

MAN'S THERMAL BALANCE IN WARM ENVIRONMENTS

QUARTERMASTER RESEARCH & DEVELOPMENT CENTER
ENVIRONMENTAL PROTECTION RESEARCH DIVISION

JULY 1956

NATICK, MASSACHUSETTS

HEADQUARTERS QUARTERMASTER RESEARCH & DEVELOPMENT COMMAND
OFFICE OF THE COMMANDING GENERAL
NATICK, MASSACHUSETTS

13 August 1956

Major General Kester L. Hastings
The Quartermaster General
Washington 25, D. C.

Dear General Hastings:

This report, "Man's Thermal Balance in Warm Environments," presents a theoretical consideration of the roles of physical activity, environmental factors, and qualitative characteristics of clothing in determining the total effect of hot weather on the operational effectiveness of the soldier. The information and concepts developed in the report have direct application as guidance in the design and development of fabrics for hot climate clothing. For the first time, it has been demonstrated how the qualitative characteristics of clothing can alter or modify the heat stress on man resulting from extreme combinations of temperature and humidity.

Sincerely yours,

C. G. Calloway
C. G. CALLOWAY
Brigadier General, USA
Commanding

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EP-30

HEADQUARTERS QUARTERMASTER RESEARCH & DEVELOPMENT COMMAND
Quartermaster Research & Development Center, US Army
Natick, Massachusetts

ENVIRONMENTAL PROTECTION RESEARCH DIVISION

Technical Report
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MAN'S THERMAL BALANCE IN WARM ENVIRONMENTS

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FOREWORD

Physiological heat stress in warm and hot environments, which tends to reduce man's efficiency and in severe cases causes collapse, is a problem of utmost importance in military operations in hot climates. Previous experimental work has indicated what environmental conditions impose this stress on man, but they do not indicate how. This paper, which supplies the answer not only to what conditions cause stress but also how, gives a much clearer understanding of the phenomena involved.

In addition to indicating the significance of environmental factors such as temperature, wind, and humidity, and physiological factors such as metabolism and sweat production, this paper indicates significant clothing factors. This consideration of the interaction of clothing factors and heat stress is new and of special interest to the Quartermaster Corps in the design of hot- and warm-weather clothing.

AUSTIN HENSCHEL, Ph.D.
Chief
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Approved:

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Scientific Director
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ABSTRACT

A theoretical analysis of the factors influencing stress in warm and hot environments is developed using physical equations of heat and moisture transfer. Two different situations are considered, the first where all sweat is evaporated and cooling limited by sweat secretion, and the second with the skin wet where cooling is limited by the amount of sweat which can be evaporated. In the former case, stress is a function of dry-bulb temperature alone and depends on the amount of sweat secreted, which may vary considerably among individuals. In the latter case, tolerance is shown to be mainly dependent on wet-bulb temperature and depends on the vapor pressure of wet skin, which does not vary much, giving rise to critical dependence of tolerance on wet-bulb temperature. Consideration is also given to the practical case of complete evaporation from some areas of the skin and incomplete evaporation from others. Graphical presentation is used to demonstrate the separate and combined effects of various environmental factors and to indicate how clothing alters these effects. The theoretical results are shown to agree with the experimental findings of others.

MAN'S THERMAL BALANCE IN WARM ENVIRONMENTS

1. Introduction

It has been recognized that the physiological sense of warmth is not always closely correlated with environmental temperature. Other factors, such as wind and humidity, have an effect. Haldane(7) in 1905 recognized the effect of humidity and suggested that wet-bulb temperature was a critical factor. He also observed that tolerance to high wet-bulb temperature rose with increasing air movement. Since that time, observations have been made in deep mines(3,13) and physiologists have worked in rooms where controlled conditions were possible(5,11,15). Houghton and Yaglou(8) in a series of papers introduced the concept of "effective temperature" by which the subjective comfort of individuals was used to rate the environment. "Effective temperature" is still widely used although Yaglou(19) himself has questioned its accuracy. The experiments of Robinson *et al*(11) have indicated environments of "equal physiological effect." More recently, McArdle *et al*(9) have produced a nomogram relating sweat rate, which they consider as an index of heat stress, to temperature, humidity, air movement, radiation, and metabolism for both nude and clothed man.

While all these experiments yield data which are descriptive of the ways in which various environmental factors affect man, they frequently do not explain the reasons for these results. Such information can be obtained by setting up the equations of heat transfer between a heated, moistened surface representing the skin, and various environments. This approach is followed here to show the separate and combined effects of environmental variables on factors associated with heat stress. Throughout the paper it is pointed out how the theoretical relationships compare with observed phenomena.

2. Basic Equations

The basic equations(18) which apply to a simple idealized physical model of the human being in equilibrium are as follows:

$$H = H_e + H_a + H_r \qquad (1a)$$

$$H = k\left[\frac{S}{c}(P_s - P_a) + (T_s - T_a)\right] + R\,(T_s - T_r) \qquad (1)$$

$$H_e = k\,\frac{S}{c}(P_s - P_a) \qquad (2)$$

$$H_a = k\,(T_s - T_a) \qquad (3)$$

$$H_r = R\,(T_s - T_r) \qquad (4)$$

where

H = net heat loss from the skin surface to the environment (kg-cal/m^2/hr)

H_e = evaporative heat loss from the skin surface (kg-cal/m^2/hr)

H_a = convective and conductive heat loss from the skin surface(kg-cal/m^2/hr)

H_r = net radiant energy loss from the skin surface (kg-cal/m^2/hr)

T_s = the skin temperature (°C)

P_s = the skin vapor pressure (mm. Hg)

T_a = the ambient air temperature (°C)

P_a = the ambient vapor pressure (mm. Hg)

T_r = mean radiant temperature of the surroundings (°C)

k = thermal conductance between skin surface and ambient air(kg-cal/m^2/hr/°C)

S = the negative reciprocal of the slope of the wet-bulb lines on a psychrometric chart (°C/mm)

c = the inverse ratio of the moisture permeability of the clothing to that of an air film of equal conductance (dimensionless)

R = a coefficient of radiant energy exchange (kg-cal/m^2/hr/°C)

In addition to these symbols, others used in this paper are:

H_e' = evaporative heat loss from the skin surface when all sweat is evaporated (kg-cal/m^2/hr)

RH_s = relative humidity at the skin surface (%), i.e., vapor pressure of the skin divided by saturated vapor pressure of pure water at the same temperature, multiplied by 100 (c f.,Gagge(6)).

P_s' = maximal vapor pressure at the skin surface (mm. Hg), in this paper assumed to be at 90% RHs

T_w = wet-bulb temperature of the ambient air (°C)

P_w = saturated vapor pressure of water at T_w (mm. Hg)

Equation (1a) states that the heat loss from the skin is equal to the sum of the evaporative, convective, and radiative heat losses (negative values are used to denote heat gains). Equation (1) is derived by substituting in Equation (1a) the values of H_e, H_a, and H_r as given in Equations (2), (3), and (4).

If one assumes equilibrium conditions so that the body is not storing heat, then H is equal to the metabolic heat minus energy dissipated such as that from the lungs and that converted into mechanical work. These last two factors can be estimated if required.

Equation (3) is a simple statement that convective heat transfer is proportional to temperature difference $(T_s - T_a)$ with k the constant of proportionality.

Equation (4) is a first approximation of Stefan's law, and is reasonably correct for small differences between T_s and T_r(2). Assuming that the skin acts as a black body with 70% of its surface area involved in radiation exchange(16), the value of R is 4.00 kg-cal/m^2/hr/°C when both temperatures are very close to 35°C and 4.346 when one is 35°C and the other 50°C. This is a difference of less than 10 percent for a 15°C range.

Evaporative heat transfer as given in Equation (2) is seen to be proportional to vapor pressure difference between skin and ambient air, the proportionality factor being $k\frac{S}{c}$. To derive the quantity $k\frac{S}{c}$, let it be represented by $Ƶ$ and apply Equation (1a) to a wet-bulb thermometer. H then will represent conduction along the stem of the thermometer, and H_r will represent radiant energy exchange between the bulb and its surroundings. If the wet bulb is in a rapidly moving stream of air, both H_a and H_e become large and H and H_r negligible by comparison. Then Equation (1a) becomes

$$0 = Ƶ(P_s - P_a) + k(T_s - T_a)$$

$$\text{or } \frac{Ƶ}{K} = \frac{T_a - T_s}{P_s - P_a}$$

In these circumstances, T_s and P_s have the particular values T_w and P_w and

$$\frac{Ƶ}{k} = \frac{T_a - T_w}{P_w - P_a}$$

By definition, $\frac{T_a - T_w}{P_w - P_a}$ equals S. This quantity S is almost constant since the wet-bulb lines on a psychrometric chart are almost straight and parallel. Tables are available from which its value may be calculated(4) but for normal conditions its value can be considered as 2.00°C per mm. Hg.

For an uncovered surface, $H_e = kS(P_s - P_a)$. The wick on the wet bulb thermometer is not considered as a covering since it is at the same temperature as the thermometer and water extends to its outer surface. If a dry covering is placed over the wick, it will, in general, reduce the moisture permeability more than would an air layer of equivalent conductance. The factor c is introduced to account for this when considering covered surfaces. For air, the value of c is 1 but for clothing c (which is a resistance factor) is generally greater than unity and increases as the permeability of the clothing to moisture is reduced.

3. Situations (wet/dry skin) limiting cooling power of sweat.

Before proceeding farther it would be well to examine Equation (2) and the parameters involved in more detail. If the man is evaporating all the sweat he is secreting, then H_e will have the particular value H_e' which equals the latent heat of evaporation times the amount of sweat secreted. H_e' can, therefore, be considered the potential cooling power of sweat. When sweat is secreted at a constant rate and all evaporated, $(P_s - P_a)$ will be constant for any given value of kS/c. It follows that as ambient humidity, P_a, increases, the vapor pressure of the skin, P_s, also increases. When P_s reaches its maximum value, $(P_s - P_a)$ can no longer remain constant with increasing P_a, and H_e must become less than H_e'. When this occurs the skin is wet rather than dry, and unevaporated sweat accumulates on its surface. Hence cooling by the evaporation of sweat is limited by one of two alternative situations. The first is when cooling is limited by the supply of sweat but potentiality for evaporation is ample. The second is when sweat secretion is in excess of that which the environment can remove. These two situations will be referred to as dry-skin and wet-skin conditions, respectively. When dry-skin conditions occur, Equation (1) becomes

$$H = H_e' + k(T_s - T_a) + R\,(T_s - T_r) \tag{6}$$

and when the skin is wet it becomes

$$H = k\left[\frac{S}{c}\,(P_s' - P_a) + (T_s - T_a)\right] + R\,(T_s - T_r) \tag{7}$$

a. <u>Environmental and clothing factors under dry-skin conditions</u>.

Under dry-skin conditions, Equation (6), the heat removed from the skin is independent of ambient humidity and the permeability of clothing to moisture. If it is assumed that the mean radiant temperature, T_r, is equal to ambient air temperature, T_a, then the only environmental factors which affect H are the environmental temperature and the wind speed, which affects k. k is also affected by the insulation of the clothing. H_e' is a physiological factor which depends on sweat rate. Because sweat rates are variable, the amount of heat dissipated by different people varies in any one environment. In consequence, physiologists have not yet been able to establish the upper limit of tolerable dry-bulb temperature in very dry environments in which equilibrium can be maintained.

b. <u>Environmental and clothing factors under wet-skin conditions</u>.

In Equation (7) the quantity H is independent of sweat rate. The heat dissipated by both evaporation and convection is directly proportional to k. That is, H can be increased by increasing k, which can be achieved either by increasing wind speed or decreasing clothing insulation. If c is equal to 1, i.e., nude man, then because $T_a = T_w + S\,(P_w - P_a)$, Equation (7) can be put in the form:

$$H = k\left[S\,(P_s' - P_w) + (T_s - T_w)\right] + R\,(T_s - T_r) \tag{8}$$

If the radiation factor $R\,(T_s - T_r)$ is small and considered negligible, then the wet-bulb temperature is the only environmental factor affecting heat dissipation with wet-skin conditions with the exception of k, which increases with air movement. Hence, as Haldane observed(7), tolerance to hot-wet conditions is a function of wet-bulb temperature, and higher wet-bulb temperatures can be tolerated if air movement is increased. However, there is a theoretical upper limit at infinite air movement when the values of P_s' and T_s correspond to the wet-bulb temperature. Since the maximum value of RH_s does not vary greatly from one person to another and since man cannot tolerate a rise in skin temperature above the normal average (33°C) of more than a few degrees, one would expect a fairly well-defined tolerable upper limit to wet-bulb temperatures at a given wind speed and metabolism.

It has been reported that one of the results of heat acclimatization is reduction in salt concentration of secreted sweat(14). Calculations have shown that this changed concentration does not appreciably affect the vapor pressure of the sweat. However, when conditions are such that a large proportion of the secreted sweat is evaporated, that which remains may become quite concentrated with accompanying lower vapor pressure. Under such conditions more dilute sweat will assist in maintaining a high P_s' by delaying the accumulation of salts. Mopping the brow serves the same purpose by removing concentrated sweat.

4. Graphical representation of relationship between environmental factors and heat dissipation from skin.

There is a graphical method of interpreting the relationship expressed in the equations for an unclothed surface, as illustrated in Figure 1.

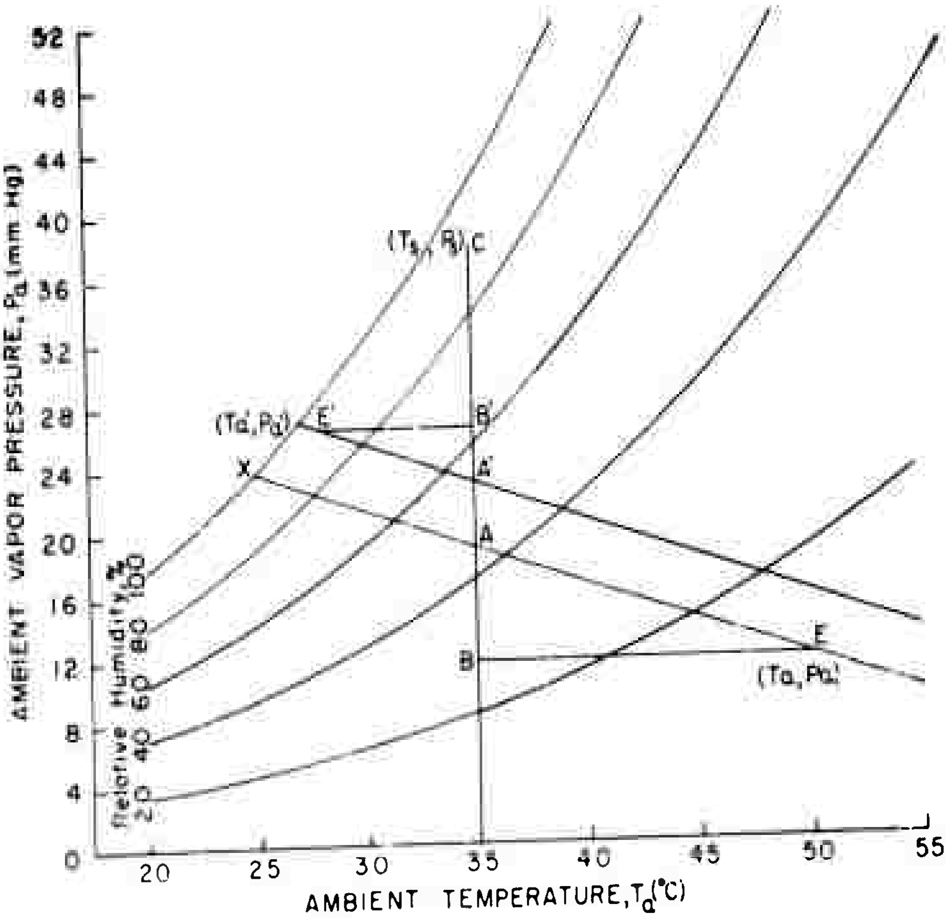

FIGURE 1: Graphical method for analyzing evaporative and convective heat exchange.

Figure 1 is a standard psychrometric chart with vapor pressure and temperature as ordinate and abscissa, respectively. Lines of equal relative humidities are plotted and marked in percent. The point C represents a skin condition at 90% relative humidity and 35°C. The point E represents an ambient condition where air temperature is above skin temperature. The line AE represents the wet-bulb line through E; its intersection with the 100% humidity line at X gives the wet-bulb temperature of the point E. The line BC is equal to $P_s - P_a$ and by Equation (2), BC = $\frac{H_e}{kS}$. The line BE is equal to $-(T_s - T_a)$ and by Equation (3) BE = $-\frac{H_a}{k}$. But $\frac{BE}{BA} = S$, and therefore BA = $-\frac{H_a}{kS}$ or AB = $\frac{H_a}{kS}$. Thus it follows that AC, which is represented by BC - BA, equals $\frac{H_e}{kS} + \frac{H_a}{kS}$. From Equation (1) $\frac{H_e}{kS} + \frac{H_a}{kS} = \frac{H-H_r}{kS}$ or AC = $\frac{H-H_r}{kS}$. That is, AC represents the heat dissipated from the skin less that dissipated by radiation. BC represents the heat dissipated by evaporation and AB the heat dissipated by convection. It will be seen that in this example AB is negative, representing a heat gain by convection. It should further be realized that if mean radiant temperature is equal to air temperature in this example, the heat dissipated by radiation will be negative or radiant energy will be received on the skin. Figure 1 also illustrates the relationships where air temperature (E') is below skin temperature and here it will be seen that A'B' is positive and convection cools the skin.

It should be noted that these lines (AB, BC, AC) represent heats divided by kS so that when wind speed (and k) is increased they represent increased heats.

5. Graphical representation of skin temperature and skin relative humidity as functions of ambient temperature and vapor pressure.

In order to give a more complete picture of the application of the heat exchange equations it is necessary to introduce what might be called an empirical physiological relationship. This is an arbitrarily assumed relationship between man's skin temperature and his sweat secretion. The authors do not imply that for an actual man sweat secretion is a function of skin temperature, although this has been assumed for the purposes of discussing the idealized man. The assumed relationship for a metabolism of 130 kg-cal/m²/hr is plotted in Figure 2, together with insensible sweat data for resting men from Pierce Laboratory(17) and the data of Robinson(11) from which the curve was derived. Figure 2 illustrates well the variability of sweat rate at any one skin temperature and, therefore, why tolerance to heat under dry-skin conditions can be so extremely variable.

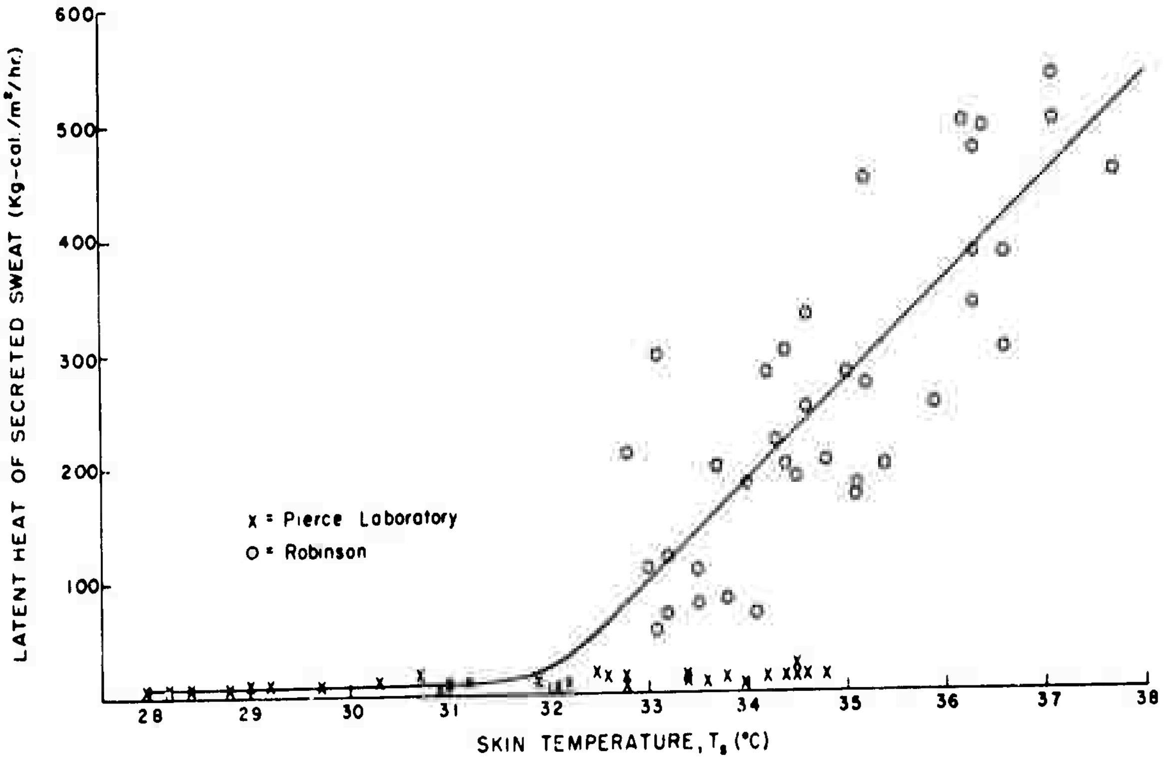

FIGURE 2: Relationship between skin temperature and sweat secretion expressed as cooling power.

By varying the values of some of the parameters in Equation (1) it is possible to see how the values of others are affected. In Figure 3, lines of constant skin temperature (solid lines) and skin relative humidity (broken lines) are plotted as functions of ambient temperature and vapor pressure. (Note: In this figure and all subsequent figures, H is assumed to be 130 kg-cal/m^2/hr to correspond with the relationship of Figure 2, maximum skin relative humidity to be 90 percent and T_r to be equal to T_a.)

It will be seen that at lower ambient temperatures where there is little sweat secreted (H_e is small), 1 degree rise in ambient temperature is required to produce about 1 degree rise in skin temperature. Heat dissipation from the skin is mainly by convection and radiation (Equations 3 and 4) and therefore (T_s-T_a) is almost constant.

a. Dry skin condition.

At low vapor pressures, with dry-skin conditions, as air temperature rises secreted sweat regulates skin temperature and it requires about a 7-degree (C) rise in ambient temperature to cause a 1-degree (C) rise in skin temperature. The spacing of equal skin temperature lines will, of course, depend on the slope of the sweat secretion-skin temperature relationship which has been selected.

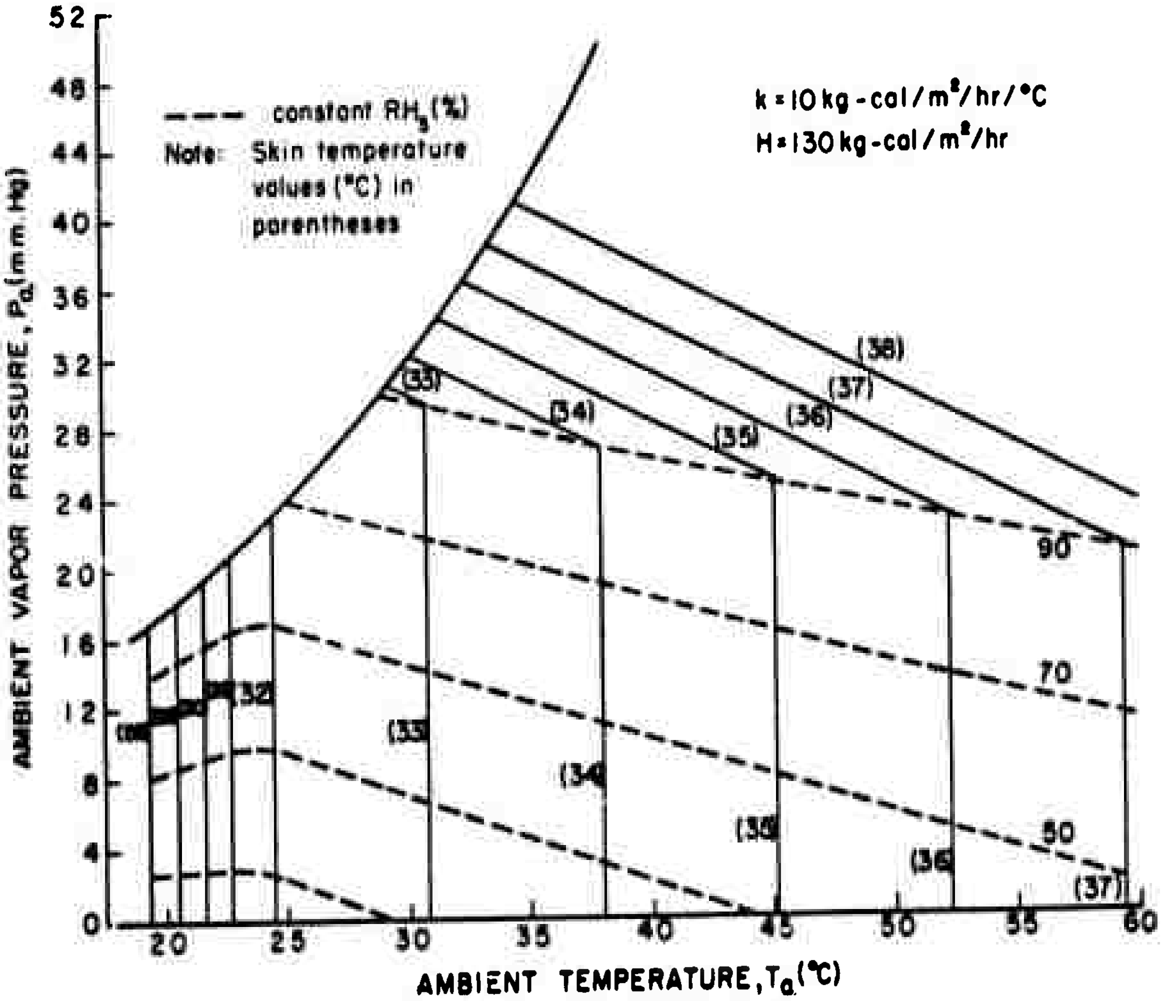

Figure 3: Skin temperatures and skin relative humidities plotted as a function of environmental temperature and humidity.

It will also depend on the value of k selected; the greater the value of k the closer the spacing of the skin temperature lines. In this region of complete evaporation, skin temperature is dependent on air temperature but not on humidity, as indicated by the fact that the lines are vertical lines. It will also be seen that a change of 20% in skin relative humidity is caused by a fixed change in air vapor pressure regardless of whether RH_s is high or low. The physiological significance of skin humidity is not apparent but may possibly be related to comfort in the psychological sense rather than heat stress in the physiological sense.

b. Wet-skin conditions.

When skin humidity reaches its maximum (90%), increase in ambient humidity can no longer result in an increase in skin humidity, and a lower ambient temperature is required to maintain skin temperature constant. That is, with P_s constant, (P_s-P_a) and H_e decrease so that to maintain H constant H_a and H_r must be increased by decreasing T_a. Although H_e decreases, the amount of sweat secreted and H_e' remain constant, and some sweat is unevaporated.

In this zone of wet skin conditions, lines of equal skin temperature are roughly parallel to the wet-bulb temperature lines of the ambient air and indicate that wet-bulb temperature is a good criterion of heat stress, as originally proposed by Haldane(7). Moreover, a 1-degree (C) rise in ambient wet-bulb temperature produces about a 1-degree (C) rise in skin temperature.

6. Graphical representation of equations holding skin temperature constant and varying other factors.

In Figure 3, skin temperature was plotted as a function of air temperature and vapor pressure using a number of values of skin temperature and holding other parameters constant. In the graphs which follow (figures 4 thru 7) only one value of skin temperature, namely 35°C, will be used and other parameters will be varied.

a. Effect of air movement.

In Figure 4, k is given 3 values of 5, 10, and 20 kg-cal/m^2/hr/°C, caused by wind speeds of about 1/2, 2 and 8 miles per hour, respectively, on a nude man(16). Under wet skin conditions an increase of k or air movement allows the same skin temperature to be maintained in a hotter environment. Under dry-skin conditions, where air temperature is above skin temperature, increased k or air movement must be compensated by a decrease in air and mean radiant temperature since H_e' is constant.

b. Effect of the clothing parameters.

Decrease of convective heating in very hot environments can be accomplished by addition of clothing, as is done by many desert tribes. Clothing has separate effects on the parameters k, R, and c in equation (1). In Figure 5 these effects are applied one at a time to demonstrate the change in ambient requirements. Curve 1 represents the ambient conditions when $k = 10$, $R = 4$, and $c = 1$ (i.e., nude man). When clothing is added, one effect is to reduce conductivity. If k is reduced to 5 with the other parameters unchanged, then curve 2 represents the ambient condition under which a skin temperature of 35°C can be maintained. Another effect of clothing is to act as a radiation shield. If R is reduced by 50% to 2.00 there is a further change to curve 3. The third effect of clothing is to decrease the permeability to moisture vapor or evaporative heat transfer.

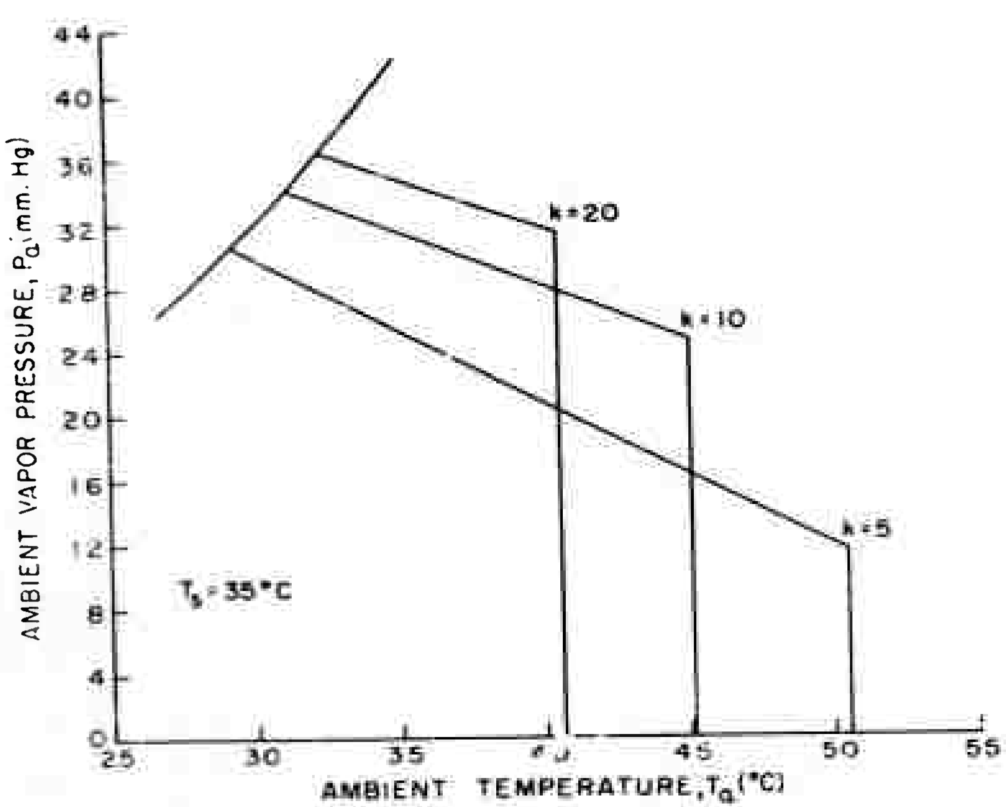

Figure 4: Effect of air movement, expressed as conductance of surface air layer, on environmental conditions causing a given skin temperature.

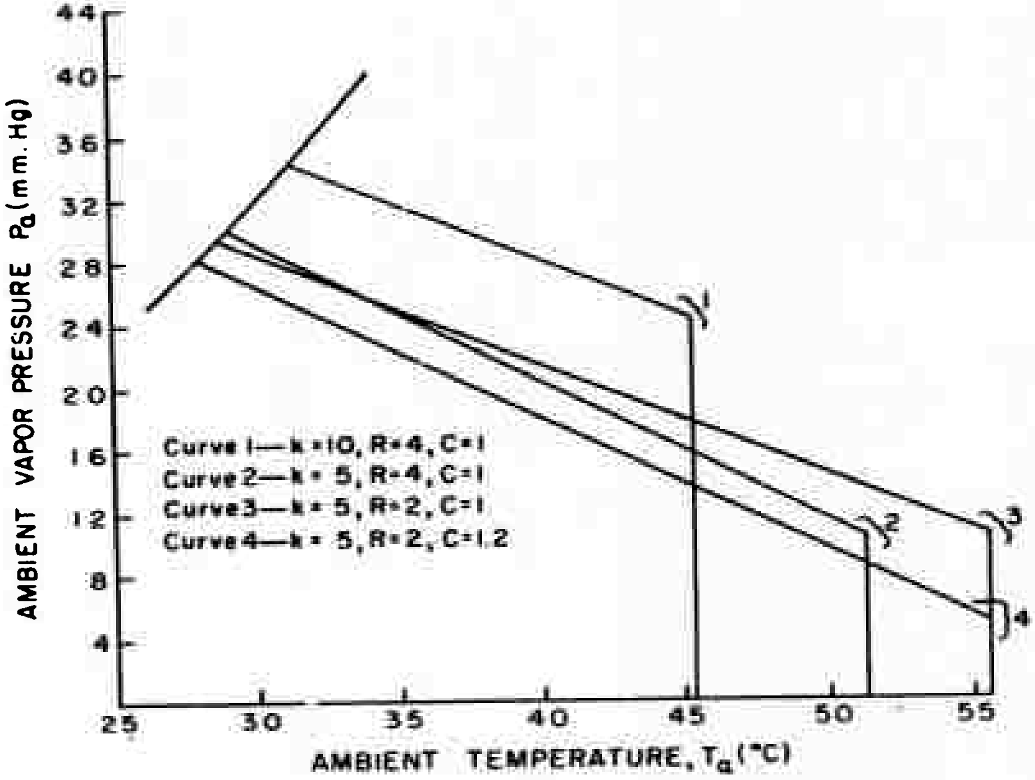

Figure 5: Effects of clothing factors on environments producing a constant skin temperature.

Curves 1 and 2—effect of reducing convection.
Curves 2 and 3—shielding effect of clothing from low temperature radiation.
Curves 3 and 4—effect of increasing resistance to moisture transfer.

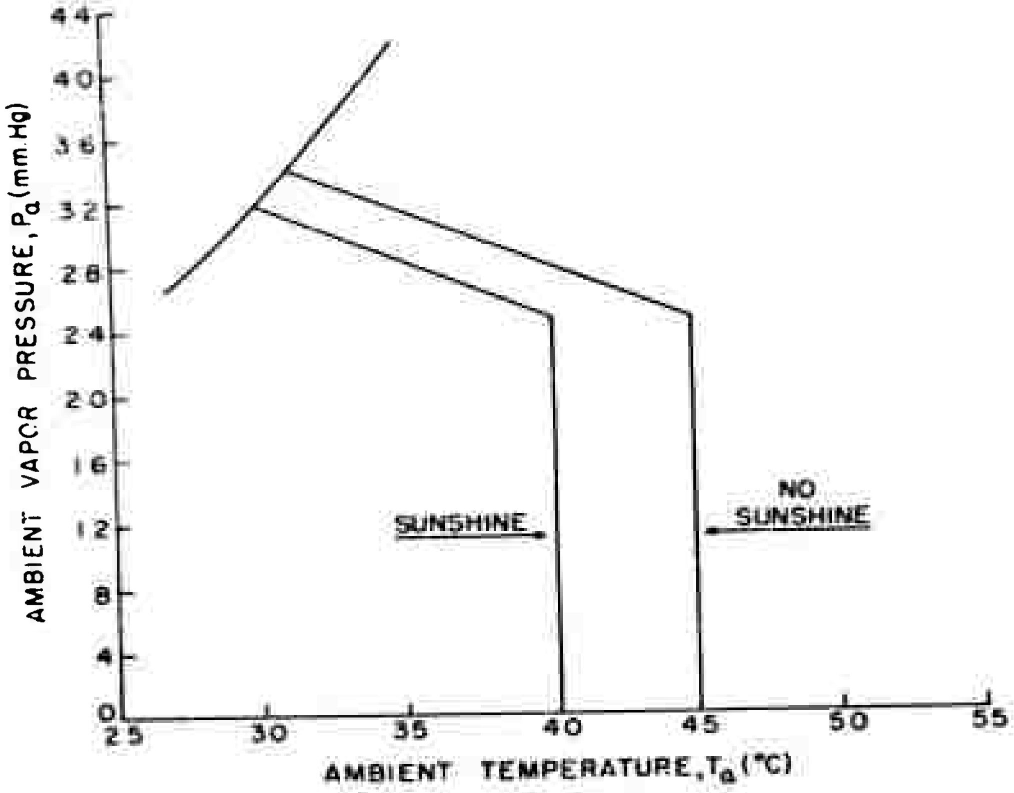

Figure 6: Effect of sunlight on environments producing a constant skin temperature.

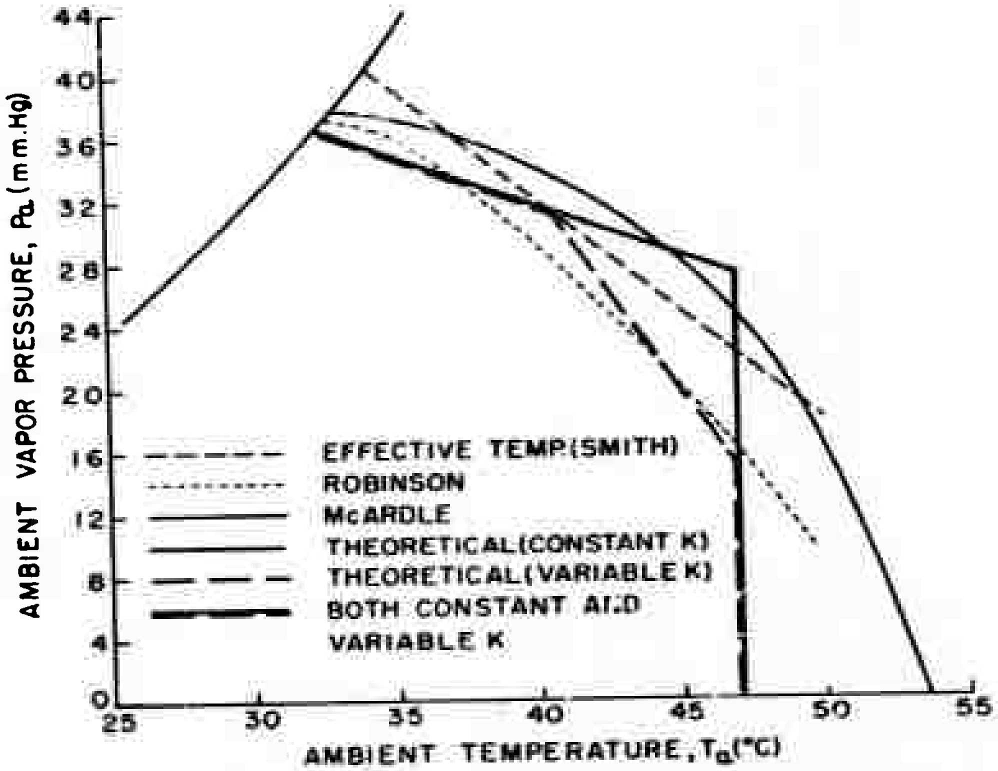

Figure 7: **Comparison of theoretical curves with experimental indices of other workers.**

When ambient temperature is below skin temperature, a decrease in radiation losses allows an increase in evaporative or convective losses and a decrease in ambient humidity. Similarly, when ambient temperature is above skin temperature, decreased radiant heat gains allow higher humidities.

The decrease in permeability to moisture, as indicated by the shift from curve 3 to curve 4, has no effect when dry-skin conditions occur, since H_e is limited by sweat secretion and not the evaporative power of the air. Under wet-skin conditions where evaporative power of the air is the critical factor, any reduction in moisture permeability will reduce this evaporative power and require lower ambient temperatures or humidities.

This analysis indicates three desirable factors in warm-weather clothing: first, that it be as permeable to moisture as possible; second, that it be a good radiation screen when ambient temperature is above skin temperature but a poor radiation screen when it is below, and third that it have the appropriate insulation value, k. When wet-skin conditions occur, it is advantageous to increase k or decrease clothing and when dry-skin conditions occur, to increase clothing.

c. Effect of solar radiation.

In the equations given above, allowance was made for long wave radiation. However, sunlight comes from a source at such a high temperature that it contributes a constant heat load. Hence a constant term for solar radiation would have to be added in Equations 1 and 1a with the result shown in Figure 6. In calculating the curves in Figure 6 it was assumed that the intensity of incident radiation was 600 kg-cal/m^2/hr, that 50% of this was effective in heating a man and that a man's shadow area on a surface at right angles to the sunlight was 25% of his surface area. It will be seen that the effect is simply to shift the curve by about 5°C at any vapor pressure. That is, sunlight can be considered equivalent to a rise in dry-bulb temperature; however, a change in air movement will have an effect on the amount of displacement of the curve, the displacement being less the greater the value of k.

7. Comparison of theoretical with experimental data.

The theoretical results show agreement with the experimental curves obtained by other workers as shown in Figure 7. The experimental curves are a curve of "equal physiological effect" derived from the work of Robinson et.al(11), one taken from the nomograph of McArdle et al(9) for equal sweat rate and one based on "effective temperature" as adjusted for metabolism by Smith(12). Each experimental curve was derived for conditions with wind speed, radiation, and metabolism as comparable as possible, and the theoretical curve calculated for the same conditions. The theoretical curve does not agree exactly with any of the experimental curves, but does not differ from them by any more than the experimental curves differ among themselves. In general shape the theoretical curve agrees best with the curve taken from McArdle's data. However, it has a sharp corner which none of the other curves have. The sharp corner shown in the calculated curve may be cut off by assuming that the value of k is not uniform over the surface. For an actual man the conductivity is continuously variable over the skin surface and is generally least in axillae and crotch areas and highest in exposed areas. For simplicity in showing the effect of a variable k on the shape of the curve, a surface has been assumed to have a value of k = 6.5 kg-cal/m^2/hr/°C over one half, and a value of k = 19.5 kg-cal/m^2/hr/°C over the other half (mean value of k = 13 kg-cal/m^2/hr/°C). The resultant curve is shown as the heavy dashed line in Figure 7. The heavy solid line is for a uniform value of k = 13. It will be seen that the effect of the variable value of k is to cut the corner off the original curve. The vertical line up to about 15 mm ambient vapor pressure represents a dry-skin condition on both areas. The line cutting off the corner represents a dry-skin condition on the area where k = 19.5 kg-cal/m^2/hr/°C and a wet-skin condition on the area where k = 6.5 kg-cal/m^2/hr/°C. The rest of the curve at high humidities represents a wet-skin condition over both areas. If a greater number of values of k were chosen, the curve would have more sections and approach a smooth curve such as is found experimentally. The quantity k is, of course, not the only factor which varies over different areas of the skin; skin temperature (T_s), sweat rate (H_e'), radiation (R) and so forth, also could be considered variable. Thus the more closely the theoretical model approximates the human being, the more closely will the theoretical results approach those found experimentally. Figure 7 also indicates the fallacy of assuming a uniform value for a variable quantity at its average.

In the development of the theory up to this point, the effects of different environmental and physiological variables have been considered, with the exception of metabolism. There is no reason to expect that the sweat rate vs. skin temperature relationship which was assumed for one metabolism (H = 130 kg-cal/m^2/hr) will hold for another. In fact experimental evidence indicates that it does not. Curves can be plotted for other values of metabolism but their relative positions will depend on the skin temperature-sweat rate relationship which is chosen.

8. Summary and Conclusions.

The purpose of this paper is not to establish the stress or limits of tolerance of man under any given set of environmental clothing and physiological variables. This has already been done(1). It is rather to interpret and clarify in a qualitative manner the part played by each variable in determining the heat exchange with the environment. The method is not capable of giving accurate predictions of stress because the physical model selected does not sufficiently approximate the surface of the human being.

Similarly it can be shown by a simple application of Equation (8) that the energy exchange in the lungs is a function of the wet-bulb temperature of the air as found by McCutchan and Taylor(10). The theory also establishes that there are three ways in which clothing modifies the heat exchange with the environment. The critical criteria in hot weather clothing design are to have the coefficient C as close to unity as possible, to have the coefficient R large when mean ambient temperature is below skin temperature but small when it is above skin temperature, and to adjust insulation or the value of k as required by the environment and activity. The theory could also be used to determine the physiological effect of different methods of heating homes and buildings, e.g., low vs. high wall temperature combined with appropriate air temperatures. It is not advisable to use the physical theory to predict human physiological reactions where direct physiological experiments can be substituted. However, it can be used to make qualitative estimates where physiological data are not yet available.

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