THERMAL BALANCE OF THE HUMAN BODY

Thermal Balance of the Human Body and its Application as an Index of Climatic Stress

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The study of the effects of climatic stress upon the individual has occupied the attention of physiologists for the last hundred years. Since the outbreak of the present war the problem has become much more pertinent owing to the military necessity of maintaining large bodies of men in different climatic zones. Furthermore, it is frequently necessary to transport the same group from one climate to another, in which case accurate estimates of the new clothing requirements are essential.

One means of attacking the problem of developing such an index is through an analysis of the heat transfer from the body to the surrounding environment. This has been studied experimentally at the Pierce Laboratory (1) and the results extrapolated to a wider range of environmental conditions by the Research and Development Branch of the OQMG. (2) The latter report outlines the basic principles of the problem but leaves many of the details to the imagination of the reader. It is the purpose of this paper to fill in some of the omissions and to illustrate means of simplifying the calculations so that the utility of this type of index may be fully realized.

The fundamental equation for the heat balance is:

1. $M + D = E + C + R$ in which

M is the metabolic rate,

D is the change in the stored heat,

E is the evaporative heat transfer,

C is the convective heat transfer, and

R is the transfer by radiation.

This equation simply states that the quantity of heat transferred is equal to the sum of the quantities transferred through each of the avenues of heat loss. Caution must be exercised in the application of the equation as M and E are the only terms which are always positive. D, C, and R may be either positive or negative, depending upon the direction of flow. Conduction through the clothing is neglected since its inclusion would lead to counting the same quantity twice.

To clarify this point further Fig. 1, which is a diagram of a cross section of an insulated pipe, may be considered to represent a man. The interior of the pipe corresponds to the deep body tissues, the pipe wall to the surface tissues, and the insulation clothing. Surrounding the whole is a mass of moving air.

If the temperatures within the system are not changing with respect to time there is no change in the stored heat and if M represents the steady heat loss from the interior of the pipe.

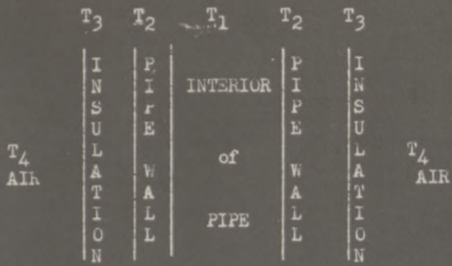

FIGURE 1.

2. $M = \dfrac{T_1 - T_2}{I_{int}} = \dfrac{T_2 - T_3}{I_c} = (T_3 - T_4)\left(\dfrac{1}{I_a} + \dfrac{1}{I_r}\right)$ in which

T_1 is the temperature of the interior,

T_2 is the temperature of the outer surface of the pipe, (skin temperature),

T_3 is the temperature of the outer surface of the insulation, (clothing layer),

T_4 is the temperature of the atmosphere,

I_{int} is the thermal resistance of the pipe wall, (Surface tissues),

I_c is the thermal resistance of the insulation, (clothing layer),

I_a is the thermal resistance to the flow of heat by convection from the surface of the insulation, and

I_r is the resistance to the flow of heat by radiation from the surface of the insulation.

The te peratures T_1 and T_4 may be accurately measured regardless of whether the figure represents a pipe or an approximation to a man. T_2 may be measured, but less accurately, while T_3 is not readily obtained. I_a and I_c may also be measured, but I_r must be obtained from other data.

Eliminating T_3 from eq. 2 results in:

3. $M = \dfrac{T_2 - T_4}{I_c + \dfrac{1}{\dfrac{1}{I_a} \div \dfrac{1}{I_r}}}$

Now, I_a, I_r and T_4 are environmental factors for their values may be determined when the air temperature, wind velocity, atmospheric pressure, and the temperature of the surroundings are known. M and T_2 are internal variables whose values are set by the conditions of the problem, and I_c is a variable which may be increased or decreased to provide the necessary protection. For instance, if the environment together with the rate of heat production are specified and T_2 must remain above some limiting temperature, the value of I_c may be found from eq. 3 which will maintain T_2 at the limiting value. The value of I_c necessary to establish equilibrium becomes a measure of the severity of the environment and as such is an index of climatic strain.

Consider the situation in which I_c is either zero or possesses some definite value. Consider also that T_2 has a fixed upper limit which cannot be safely exceeded. Then, for any environment there will be a maximum value for M which cannot be exceeded without increasing T_2 above its safe limit. This maximum value of N is also an index for defining the severity of climatic strain.

Either of these indices could be used but the heat transfer from human beings, while it is analogous to the loss of heat from pipes, also takes place through other channels. These other factors which must be considered are:

1. The evaporation loss E_s from the skin.

2. The evaporation loss E_l from the lungs

3. The heat A transferred by warming or cooling inspired air.

Items 2 and 3 represent direct transfer from the interior of the body and may be accounted for in eq. 2 by replacing M by $M - E_l \pm A$.

The loss of heat through evaporation from the skin is more difficult to handle because of the need for specifying where the evaporation occurs. If the clothing is dry and the evaporation proceeds at the skin surface eq. 2 must be replaced by:

$$4. \quad M - E_l \pm A = \frac{T_1 - T_2}{I_{int}} = E + \frac{T_2 - T_3}{I_c} = E + \left(\frac{1}{I_a} + \frac{1}{I_r}\right)$$

If, on the other hand, the clothing is saturated and the evaporation takes place at the outer surface eq. 2 becomes:

$$5. \quad M - E_l \pm A = \frac{T_1 - T_2}{I_{int}} = \frac{T_2 - T_3}{(I_c)} = E + (T_3 - T_4)\left(\frac{1}{I_a} + \frac{1}{I_r}\right)$$

in which the brackets have been placed around I_c to indicate that its value has been changed because of the saturation with sweat.

In the preceding discussion the units have not been mentioned, but the equations hold for any consistent set of units. If a mixed system is used appropriate numerical factors must be inserted where necessary.

The temperature of the clothing surface T_s may be eliminated from eq. 4 with the result:

$$4a. \quad M - E_1 + A = E + \frac{3.09\,(T_2 - T_4)}{I_{clo} + \dfrac{1}{\dfrac{1}{I_a} - \dfrac{1}{I_r}}}$$

in which I_c has been replaced by I_{clo} and all resistances should be expressed in clo units, temperatures in degrees F., and energies in Kg. Cals. per square meter per hour. The factor 3.09 is a conversion constant brought in by the mixed units.

The same may be done with eq. 5 resulting in:

$$5a. \quad M - E_1 \pm A = \frac{E}{1 + \dfrac{(I_{clo})}{I_a + I_r}} + \frac{3.09\,(T_2 - T_4)}{(I_{clo}) + \dfrac{1}{\dfrac{1}{I_a} + \dfrac{1}{I_r}}}$$

in which the units are the same as in eq. 4a and the brackets have been placed around I_{clo} to indicate that the resistance of wet clothing is to be used.

Frequently it is convenient to express these equations in terms of thermal conductances in which case equations 4a and 5a become:

$$4b. \quad M - E_1 \pm A = E + \frac{T_2 - T_4}{\dfrac{1}{C_{clo}} + \dfrac{1}{C_a + C_r}}$$

$$5b. \quad M - E_1 \pm A = \frac{E}{1 + \dfrac{C_a + C_r}{C_{clo}}} + \frac{T_2 - T_4}{C_{clo} + \dfrac{1}{C_a + C_r}}$$

in which C_{clo} is the thermal conductance of the clothing in Kg. Cals/m^2/°F/hr., C_a and C_r are the surface conductances due to convection and radiation respectively in the same units, temperatures are expressed in °F., and energies in Kg. Cals/m^2/hr. Conductances in these units are related to resistances in clo by the relation:

6. $$\text{Conductance} = \frac{3.09}{\text{resistance in clo}}$$

Upon comparing equation 4b with 5b, it is apparent that the values assigned to E are not necessarily the same. The letter E merely represents the quantity of heat lost through evaporation and may have any value consistent with the assumptions that in eq. 4b the evaporation is proceeding at the skin surface and in eq. 5b the evaporation occurs at the surface of the clothing. For that reason the factor $\frac{1}{1 + \frac{C_a + C_r}{C_{clo}}}$ multiplying E in eq. 5b should not be interpreted as an evaporative efficiency factor. Instead this term is actually a measure of the change in heat transfer by radiation and convection caused by the change in T_3.

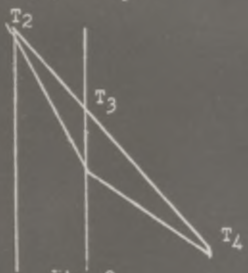

Fig. 2

Figure 2 illustrates the point. If the clothing layer between T_2 and T_3 is considered to be saturated, but no evaporation is taking place, the temperature gradient will be as shown by the solid line. Suppose now that evaporation occurs at the clothing surface. Because of the increased heat flow through the clothing, the temperature gradient must increase, and, if T_2 and T_4 are constant, T_3 must fall and reduce the value of $(T_3 - T_4)$. The decrease in the differential decreases the convective and radiative transfer.

Equation 5 shows, however, that it is possible to compute the total loss by evaluating the effect of convection, conduction, and radiation exactly as though evaporation were neglected and then compensate for this neglect by multiplying E by the term $\frac{1}{1 + \frac{C_a + C_r}{C_{clo}}}$ E must be evaluated as the evaporation from a surface at the temperature T_3. T_3 can only be expressed in terms of E or M, but its value together with that of E may be found from equation 5 by trial and error.

So far these equations are quite general, the only assumptions that have been made concern the location of the area from which evaporation occurs and that the effect of radiation can be expressed in terms of conductances or resistances. The latter is equivalent to assuming that there is no solar or sky radiation and that surrounding temperatures are approximately air temperature. For conditions in which radiation must be considered separately equations 4b and 5b become:

4c. $$M - E_1 \pm A = E + \frac{T_2 - T_4}{\frac{1}{C_{clo}} + \frac{1}{C_a}} + \frac{R}{1 + \frac{C_a}{C_{clo}}}$$

$$5c.\quad M - E_1 \pm A = \frac{E + R}{1 + \frac{C_a}{C_{clo}}} + \frac{T_2 + T_4}{\frac{1}{C_{clo}} + \frac{1}{C_a}}$$

in which R is considered positive if its net effect results in a transfer of heat from the body to the surroundings and negative if the reverse is true. In these equations the factor $\frac{1}{1 + \frac{C_a}{C_{clo}}}$ which multiplies R in equation 4c and R + E in equation 5c enters for precisely the same reasons as the factor $\frac{1}{1 + \frac{C_a + C_r}{C_{clo}}}$ multiplying E in eq. 5b.

Equations 4c and 5c may also be used with equation 2 to eliminate T_2 or skin temperature. When this is done we have the following:

$$4d.\quad M - E_1 \pm A = \frac{3.09\ (T_1 - T_4) + E\ (I_{clo} + I_a) \quad RI_a}{Int + I_{clo} + I_a}$$

$$5d.\quad M - E_1 \pm A = \frac{3.09\ (T_1 - T_4) + (E + R)\ I_a}{Int + I_{clo} + I_a}$$

Equations 4d and 5d express the thermal balance of the body as a function of the temperature differential between the interior of the body and the atmosphere, the various resistances of the system, and evaporation and radiation.

If each of these individual factors may be measured, equations 4d and 5d may be used to determine an index of climatic strain. Exactly which term is used to define an index may depend upon the particular problem. For cold weather conditions I_{clo} appears to be the most logical choice, which is equivalent to describing the environment in terms of the protection required to sustain a given metabolic rate. For hot weather conditions there appear to be two choices, either of which would be satisfactory. For given atmospheric conditions, E may be found and the maximum value of the metabolic rate used as an index of the severity of the climate, or if the metabolic rate is fixed the required value for evaporation may serve as an index of climatic strain.

Burton (3) has discussed these possibilities and has shown that there is no simple relationship existing between the two except at limiting metabolic rates.

The primary reason for the complexity found by Burton arises from the attempt to evaluate evaporation in terms of comfort or wetted area and also the effect of clothing on evaporative heat loss. Furthermore, the evaporative loss and the metabolic rate are closely related since in a given environment an increase in metabolic rate will cause an increase in internal temperature which will be followed by an increase in skin temperature and an increase in evaporation.

The Evaluation of C_a and I_a

The basic determinations of these factors for the human body both clothed and unclothed were made by Winslow, Herrington, and Gagge (4) for wind velocities between 8 and 100 feet per minute and in a relatively restricted temperature range. Burton (5) extended these values and calculated I_a for various altitudes or atmospheric pressures and showed that the effect of temperature was small.

The Research and Development Branch of the OQMG developed the relation for C_a:

7. $$\frac{C_a D}{k} = 1 + 0.407 \left(\frac{DVR}{u}\right)^{\frac{1}{2}} + .00123 \left(\frac{DVR}{u}\right)$$ in which

C_a is the surface conductance

k is the thermal conductivity of air at the interfacial temperature

R is the density of air at the interfacial temperature

u is the viscosity of air at the interfacial temperature

D is the cylinder diameter

V is the wind velocity

and any consistent system of units may be used to evaluate each of the terms.

Cylinders were used for this derivation for their shapes more closely approximates that of the human body than either spheres or flat planes which are the only other forms for which convective constants are known over a wide range of wind velocities. Comparison of this equation with physiological data indicates that the convective heat loss from the body is very close to that of a three inch cylinder within the limits of the experimental conditions. For this diameter the expression deviates from experimental results of cylinders by less than 5% for wind velocities between one tenth and fifty miles per hour.

Equation 7 in spite of its complexity possesses the advantage that the effect of pressure and temperature variations can be calculated for any cylinder diameter, and both are functions of the diameter of the cylinder under test. Variations in the moisture content of the atmosphere will also cause small changes in the surface conductance. The available data is insufficient to provide an accurate estimate of these changes but they are probably of the order of 1% or less. The density of the atmosphere increases with an increase in moisture content, but this is offset by an increase in viscosity. The thermal conductivity of water vapor at 212°F is approximately 30% less than that of dry air so that in the concentrations usually found in the atmosphere its effect must be very small.

Fig. 3 shows the relation between the convective heat loss and wind velocity for a three inch diameter cylinder with surface temperatures of 0°F, 60°F, and 120°F. The factors used in this calculation are given in Table I and have been taken from McAdam (6) and International Critical Tables.

Table I

FACTORS USED IN CALCULATION OF SURFACE HEAT TRANSFER COEFFICIENTS

Altitude Ft.	Temp. °F.	Thermal Conductivity of Air B.t.u./hr./ft./°F/ft.	Density of Air lb./ft.	Viscosity of Air lb./hr./ft.
0	0	.0132	.0863	.0392
0	60	.0147	.0763	.0433
0	120	.0161	.0684	.0472
5,000	42.2	.0143	.0656	.0421
10,000	24.3	.0138	.0561	.0409
15,000	6.5	.0134	.0479	.0397
20,000	-10.6	.0129	.0401	.0385

The same figure also shows a plot of the equation used by the Pierce Laboratories as a solid line within the region covered by experimental conditions and as a dotted line for extrapolation. The R.D.B. value for C_a is appreciably higher at wind velocities above 10 miles per hour, and there are reasons to suspect that even this figure may be low.

It is difficult to realize that the body loses heat at the same rate as a three inch diameter cylinder when both are at the same temperature and exposed to the same conditions. However, a man may be considered to be an assemblage of cylinders of various sizes and, as shown in Fig. 4, the surface conductance per unit area for small cylinders is greater than that for large ones. Furthermore the effect of surface resistance may be considered as a motionless film between the body surface and the moving air stream. For low wind velocities this resistance will be equivalent to that of a dead air layer about two millimeters thick, so that very small diameters such as the fingers effectively will merge together to form a single larger cylinder. With increased wind velocity the insulating air film will decrease in thickness so that it may well be that the body loses heat at the same rate as a cylinder but that there is a decrease in the effective diameter as the wind velocity increases.

This reasoning is very much simplified and should not be taken too seriously. Nevertheless it does point to the desirability of obtaining surface conductances from the body when exposed to high wind velocities.

The influence of altitude up on surface conductance may be found by inserting the values from Table I in equation. A change in altitude also implies a change in temperature and the values in the Table have been calculated by assuming a lapse rate of 3.56°F per thousand feet. The other factors have been corrected for both pressure and temperature change. The relation between conductance and wind velocity is shown in Fig. 5. These curves are quite similar to the ones published by Burton (5), but are expressed as conductances instead of resistances.

In fact, the surface conductance or resistances calculated from equation 7 merely substantiate the accuracy of Burton's figures since the difference between the two sets of values is of the order of 0.1 clo or less.

The Evaluation of I_{clo} and C_{clo}

These terms may be either the unknowns for which the equations are being solved or constants which are inserted in the equations. If they are being used as constants, their values for specific outfits may be found by actual test following the methods outlined by Belding et al. (7)

Another way of determining the insulating power of clothing has been proposed by Siple et al (2) who has shown that remarkably close agreement with experiment can be secured by careful measurement of clothing thickness and fit. This method is based upon the assumptions:

1. Clothing resistance is proportional to the thickness of the cloth and is the same for all conventional fabrics.

2. The effective thermal resistance of an air space within the clothing is proportional to the thickness if the space is less than one fourth of an inch thick. Air spaces greater than one fourth of an inch are considered to have the resistance of a quarter inch space.

3. The outer layer of clothing is either a good windbreak or the wind velocity is so low that its penetration into the clothing is negligable.

The first two assumptions are in good agreement with experiment and the third is merely a limitation of the conditions for which the method may be applied. Clothing resistances calculated in this way appear to be particularly useful for the following purposes.

1. To make an estimate of the insulating value of an outfit in the absence of any specific data.

2. To make an estimate of the insulation which any garment contributes to a given assembly.

3. To determine the thermal balance of an assembly for the purpose of correcting points which are too tight or too loose to give optimum protection.

4. To indicate where additional thickness may be added to improve insulation with a minimum increase in weight.

5. To evaluate the loss of local insulation at pressure points.

6. To evaluate the component parts of linen garments.

This method has recently been tested by Libet (8) who concluded that the results are probably accurate within 5 or 10%. He also discusses the limitations of the method, but finds that these are not serious and that the errors are small and tend to cancel. Again, however, the results are based on relatively few experiments and it would be desirable to have more data so that the limitations of the method may be accurately determined.

An easy way of calculating the value of the term $\frac{3.09\,(T_2 - T_4)}{(I_{clo}) + \frac{1}{\frac{1}{I_a} + \frac{1}{I_r}}}$

and $\frac{3.1\,(T_2 - T_4)}{I_{clo} + I_a}$ is through the use of line charts shown in Figs. 6 and 7. These charts are quite similar as the only difference is in the wind velocity scale which has been altered in Fig. 7 to take into account the radiation conductance of 2.6 or a resistance of 1.19 clo. If other values of radiation conductance are used they may be combined with the convective conductance and the surface resistance calculated. In this case, either chart may be used.

<u>The Evaluation of Terms Involving Radiation</u>

In attempting to calculate the radiant transfer between the body and its surroundings, three cases must be sharply distinguished. These depend upon the presence of solar radiation and if this is absent upon whether or not the radiation to the surrounding surface must be treated separately from the radiation to the surrounding atmosphere.

Case 1. The surrounding surfaces may be considered as black bodies at air temperature.

This is the only case for which the radiant interchange may be accurately calculated for Hardy (9) has demonstrated that the human skin either black or white has an emmissivity of .97 or 97% of that of a black body. Fabrics of wool, silk, or cotton also have high emmissivities which have been shown by Hutte (10) to be .80 or higher. Furthermore the surrounding surfaces indoors are generally covered with paint films or paper which have emmissivities of .80 to .95. Even aluminum paints have emmissivities between .3 and .7. These figures seem high but it must be remembered that they have been measured at approximately body temperature and that the maximum radiation intensity from an object at this temperature occurs at a wave length of 9 microns—well beyond the visible spectrum.

In any case the emmissivity of the surroundings is not greatly important because the radiant interchange between an object and a surface which completely encloses it is given by:

8. $R = D_1 S \left[(T_3)^4 - (T_4)^4 \right] / \left[\frac{1}{E_1} + \frac{D_1}{D_2} \left(\frac{1}{E_2} - 1 \right) \right]$

in which B_1 is the emmissivity of the enclosed surface

D_1 is the area of the enclosed surface

B_2 is the emmissivity of the enclosing surface

D_2 is the area of the enclosing surface

T_3 is the surface temperature of the clothing

T_4 is the temperature of the surrounding air and surfaces

S is the Stefan Boltzman constant

R is the net radiant interchange

When B_1 and B_2 are unity this reduces to the customary form of the Stefan Boltzman law. Also when D_2 is much larger than D_1 the second term in the denominator approaches 0 and may be neglected. Consequently the net radiant transfer is controlled primarily by the emmissivity of the smaller surface.

The numerator of equation 4 may be readily evaluated from Fig. 8, which is a graph of the value of $D_1 S T^4$ when D_1 is equal to 1 sq. meter. This is the quantity of heat radiated from a black body at the temperature T to surroundings at absolute 0. The quantity of heat received from the surroundings at the temperature T_4 is $D_1 S (T_4)^4$ and this value may be taken from the same curve. The net interchange is equal to the difference between these values.

R so obtained is measured in Kg.Cal./M^2/hr. and is the quantity of heat radiated from a black body to black surroundings. Corrections for the emmissivities for the two surfaces can easily be made by dividing this result by the denominator of equation 8.

Radiation values obtained in this way may be substituted for R in equations 4c and 5c. This method depends upon a knowledge of the value of T_3. When T_3 is unknown C_r may be approximated from Fig. 6 by drawing a straight line through that portion of the curve which will include both T_3 and T_4. The dotted lines in Fig. 6 show three such approximations. The slope of the upper line gives a value of 3.5 for C_r and the error involved in using this value will be less than 5 Kg.Cal. per square meter per hour when both T_3 and T_4 are between 80°F and 140°F. The use of the middle line indicating a conductance of 2.6 will cause an error not greater than 10 Kg.Cal/M^2/hr. over the temperature range 5°F to 100°F and the lower line with a conductance of 1.7 will be accurate to 5 Kg.Cal/M^2/hr. or less between 20°F and -40°F.

The radiation conductance of 2.6 will be used throughout the balance of this report although more precise values may be obtained for any particular case by drawing a straight line from the curve at the temperature T_4 and the curve at an estimated value of T_3 from the approximate relation.

9. $T_3 - T_2 = \frac{1_{clo}(T_2 - T_4)}{1_a - 1_{clo}}$

The slope of this line is the radiation conductance from the clothing surface and may be substituted without change in eq. 4b and 5b or converted to I_r by means of eq. 6 and used in eq. 4a and 5a.

Case II Radiation to surrounding surfaces must be treated separately from radiation to the atmosphere

The complexity of this situation is so great that only approximate solutions may be obtained. The difficulty is caused by the atmospheric absorption of radiation from surfaces at body temperatures. The amount of absorption depends upon the path length of the beam and on the concentration of water vapor in the atmosphere. A ten foot air column at a temperature of 100°F and with a vapor pressure of 20mm. would have an emmissivity of 0.2. If the vapor pressure were reduced by one-half or the length of the column by one-half, the emmissivity would be only 0.1.

Since the emmissivity of the atmosphere changes greatly with change in vapor pressure, general expressions for the value of the radiant interchange cannot be given. Approximate values can be obtained by numerically integrating the interchange along all possible paths.

Case 3 - Solar Radiation

Solar radiation has been discussed theoretically by Blum (11), Schickele (2), and Burton (3), and some experimental data has been secured by Robinson (12). Unfortunately, these results provide only estimates of the magnitude of the radiation factor. In fact, Dr. Blum has expressed the situation perfectly when he said, "It seems to me what we need is a lot of measurements that we do not have", and present information is based almost wholly upon the value of the solar constant, together with a few measurements of atmospheric transmission, albedo, reflecting power of clothing, etc. Such measurements as are available are not sufficient for general evaluation of radiation over different parts of the globe.

The effect of the radiation term can be quite appreciable. Blum and Schickele have evaluated the radiation factor as being approximately 50 to 250 kg. calories per square meter per hour.

Burton (3) has shown that radiation may be expressed as an increment in temperature and algebraicly added to the temperature differential. Figure 2 in his report (3) illustrates the values that may be found. For the present, this is one of the easiest ways of handling the radiation problem and is probably as accurate as any other.

The most practical approach to the radiation problem appears to be from the experimental side in developing an instrument which would give, directly, the integrated effects of all radiation and such an instrument might then be used by the Weather Bureau and radiation factors measured in many places.

Evaluation of Internal Conductance

The internal conductance of the body has been measured by Dubois (13), Hardy (14), Hardy and Mittleman (15), Winslow, Herrington and Gagge (16). The measurements of these investigators were obtained in conditions of comfort, vaso constriction, and slight vaso dilation. Robinson provided the data from which conductances may be obtained a limiting conditions of heat stress. Robinson's data has been plotted in Figure 9 to show the relationship between conductance and internal temperature. It is interesting to note that the conductance changes only slightly in the range of comfort, but a large increase occurs as the internal temperature approaches maximum safe figures. This rise indicates a great increase in the rate of heat transfer which must be caused by an increased volume of blood flow.

Internal conductances must be based upon the measurement of internal temperatures, skin temperatures, and metabolic rate. At conditions of thermal strain the temperature differential is quite small and any error in the measurement of skin temperatures will cause an appreciable change in the value found for conductance. However, under these same conditions skin temperatures will be much more uniform so the probability of error is somewhat minimized. It would be desirable to have many more measurements of this factor, particularly for different types of individuals under conditions of high thermal stress.

Evaluation of Evaporation from the Lungs and Warming Inspired Air

These two terms represent direct heat losses from the interior of the body and are probably closely associated with the metabolic rate. Burton (5) assumed that the value of these two terms is 25% of the total heat production. Belding et al (7) have provided a line chart for the determination of these factors when the pulmonary ventilation is known. Unfortunately, the writer has been unable to find any figures correlating pulmonary ventilation with metabolic rate so that it seems necessary to find some other means of evaluating these factors. It will be shown later that Burton's estimate was very close to the value which may be obtained from Robinson's (22) data.

Basic studies of the evaporative constants of the human body have been made by Gagge (17) and by Winslow, Herrington, and Gagge (18). They found that at wind velocities of 17 feet per minute the maximum rate of evaporative transfer was 2.99 Kg.Cal/M^2/hr/mm. This figure was then extended to higher velocities by means of the equation:

10. $$E = 2.99\left(1 + \frac{V}{119}\right)$$ in which

E equals the evaporative transfer in Kg.Cal/M^2/hr./mm

V is the wind velocity in cm/sec

The value of the term $\left(1 + \frac{V}{119}\right)$ was taken from the work of Carrier

(19) and while this is in good agreement with experiment for small changes in wind velocity it does not provide accurate results over a wide range of velocities. The most accurate data on the evaporation from wet cylinders exposed to a transverse air flow was obtained by Powell (20) in a very carefully executed series of experiments. He found that the rate of evaporation could be expressed as:

11. $$E = 1.72 \times 10^{-7} \, (P_w - P_a) \, V^{0.6}/D^{0.4}$$

in which E is the evaporation in $gms/cm^2/sec$

P_w is the vapor pressure of the water surface in mm. hg.

P_a is the vapor pressure of the water in the atmosphere

V is the wind velocity in cm/sec

D is the diameter of the cylinder in cm.

By a suitable choice of diameter this expression may be made to coincide with the physiological data with the result:

12. $$E = 8.1 \; V^{0.6}$$

in which E is the evaporative heat transfer in $Kg.Cal/M^2/hr/mm$ and V is the wind velocity in miles per hour.

This equation agrees with the physiological experiments and also coincides with the physical experiments on the effect of wind velocity upon rate of evaporation.

The diameter required is about 14 inches which seems large when it is remembered that the body behaves as a three inch diameter cylinder for convective transfer. It must be realized, however, that the convective resistance to heat flow in still air is equivalent to a motionless film approximately 2 millimeters in thickness. The resistance to evaporative transfer is equivalent to a similar film 2 centimeters in thickness. If the radius of all parts of the body were to be increased by 2 cm., many parts would merge and the body would tend to approach the shape of a single large cylinder. Consequently, it is expected that the body will behave as a cylinder of large diameter for evaporative transfer and as a cylinder of smaller diameter for convective transfer.

Nevertheless, it would be desirable to have measurements made at higher velocities for as the thickness of the resistive film decreases with increased velocities a change in effective diamter may also be found.

As a first approximation eq. 12 may be used to evaluate the evaporation from nude men or from clothed men when the clothing is saturated. The situation becomes more complicated when the clothing is dry and the evaporation proceeds from the skin surface for then the clothing and entrapped air then interpose an additional barrier to the rate of flow.

Fourt (2) has shown that the rate of evaporation is related to the air permeability of the fabric and to the air space beneath it. Some of his results for a series of different types of cloth are shown in Fig. 10. These data may be approximated within experimental error by multiplying the evaporation from a bare surface by $\left(\frac{\text{air permeability of fabric}}{2800}\right)^{0.8}$. This term may be used to modify Powells equation to obtain one expression which relates evaporation to fabric permeability and to wind velocity. Powell's equation then becomes:

$$13. \qquad E = 8.1 \left(\frac{\text{Air permeability of fabric}}{2800}\right)^{0.5} V^{0.6}$$

in which the air permeability is measured in cubic feet/ft^2/min with a pressure drop across the fabric of 0.5 inch water. The figure 2800 used in this expression is simply the value found in the permeability test equipment when the resistance of the cloth approaches zero.

The value of E in equation 13 may be readily found from Fig. II by drawing a straight line between the appropriate point on the wind velocity scale G and the point on the vapor pressure differential scale C corresponding to the existing conditions. The point at which this line intersects scale F gives the evaporative loss from a bare surface. The effect of covering the surface may then be found by drawing a line between the loss from a bare surface and the point on the fabric permeability scale C corresponding to the type of fabric used. The intersection of this line with scale E gives the evaporative loss from beneath a dry fabric.

The evaporative loss so found assumes a wetted area of 100% and that the dry fabric covering is 1 cm. away from the wet surface. These conditions are probably never realized in practice for when the wetted area approaches 100% the clothing is wetted and some of the evaporation occurs within the cloth or from its surface. Nevertheless, these equations and the chart furnish a first approximation to the rate of evaporation and the accuracy will improve as the wetted area is diminished.

The effect of wetted area and comfort upon rates of evaporation may be easily obtained by first finding the transfer from the completely wetted surface and multiplying these values by the % wetted area. Also the same chart may be used to find any of the variables if the others are known or even to find the relation between any two if the balance are given.

Scale A and B on this figure are provided to show roughly the relation between the vapor pressure of saturated air and the temperature of the air.

Discussion

In attempting to use equations 4 or 5 or one of their variations, it must be remembered that they only state the relations that must exist for equilibrium conditions. For instance, Burton (3) has shown that the evaporation from a wet surface covered with wet clothing must be greater than from a bare wet surface.

This does not mean that adding a layer of wet clothing over a bare wet surface will increase the evaporative cooling. Instead, it means that the evaporation has become less effective since it occurs at the surface of the clothing and, consequently, a greater amount must be lost to maintain equilibrium. As used in these equations E and R are almost independent of the balance of the system. Their values are determined by other factors such as wind velocity, vapor pressure, cloudiness, etc. which do not appear explicitly.

To clarify this point further consider eq. 4d. If M is changed and the temperatures, resistances and evaporations remain constant then R must also change. But R can only vary if the reflecting power of the clothing, its temperature, or the intensity of the solar radiation is altered. Under the conditions mentioned, the equation simply states that if M is varied R must also be varied or equilibrium conditions will cease to exist. In this case, the temperatures within the system will change in the direction to restore equilibrium. Alterations of temperature within the system will also make a change in the quantity of heat stored.

E. On the other hand the temperatures of the system are definite functions of M, B, R, and the different resistances. Change any one of these terms and unless some other compensating change is made the temperatures at all points within the system will assume new values. Eq. 4d shows that there is a fixed relation between internal temperature, metabolic rate and environmental conditions. Vary either of the latter and the internal temperature will show a corresponding change. The effect is masked by the large increase in internal conductance which takes place when the environment becomes severe. Nielsen (21) has shown that the internal temperature is strongly influenced by the performance of work, but his experiments were not sufficiently complete to establish the variation of internal temperature for different external conditions. The working periods were generally one hour in duration and the temperature changes during this period are greatly influenced by heat storage.

The storage factor has not been considered but allowance may be easily made for it by adding the hourly rate of increase or decrease to M in the equations prior to 4d and 5d. The latter are suitable only for equilibrium and altering them to allow for changes in storage is much more complicated.

Exactly which of these equations is used in developing an index is dependent upon the conditions of the problem, the information available, and the information desired. The limiting metabolism may be chosen and this shows the maximum work rate which can be sustained, but gives little or no information concerning relative comfort or effeciency. The simplest way of solving the equations consists in finding E for various fixed values of the other variables. However, E is not easily related to comfort or efficiency.

Neither of these methods is wholly satisfactory but there is still another way of approaching the problem. An instrument is being developed by this section which can measure the total quantity of heat which may be accepted by the atmosphere. While there are some practical problems to be solved it is by no means impossible or even impractical. Such an instrument would give a direct measure of the value of C + E + R for a bare surface maintained at some fixed temperature. Suppose then that the thermal acceptance of the atmosphere is defined as the quantity of heat which would be lost through the skin of a nude man whose skin temperature was maintained at 97°F. If in addition, we define the thermal acceptance ratio as the thermal acceptance of the atmosphere divided by the rate of heat production a number is obtained which seems to be definitely related to the physiological variables. Fig. 12 shows the relation between the skin temperature from Robinson's data for men clothed in shorts and the thermal acceptance ratio. This data appears to be linear and when statistically analyzed forms a series of three straight lines which intersect near 96.6°F and a ratio of 1.30. This would imply that perhaps two errors had been made. First, that no account had been taken of the heat loss through the lungs, and, secondly, that the heat loss from the bare surface was in error by an amount equivalent to a change in skin temperature of .4 degree Fahrenheit. If allowance were to be made for the heat transfer from the lungs, we would expect the line to intersect at 97°F and a ratio of unity. Since no allowance was made for $E_1 + A$, it is to be expected that the intersection would occur at some point on the ratio axis greater than 1. The actual intersection at 1.30 implies that the heat transfer from the lungs is equivalent to 23% of the metabolic rate.

Statistically, this is not highly significant because the scatter of the experimental points about the lines in such that we could legitimately choose almost every point likely within the cross-hatched area of Figure 13. This area is bounded by lines which have been drawn two standard deviations away from the skin temperature line and represents the area which is common to all three sets of lines. If the same procedure is repeated for men wearing clothing, it is found that the lines relating skin temperature to thermal acceptance ratio differ only slightly in position from the lines drawn for men wearing shorts, and this difference is, in general, within two standard deviations. The area which is within two standard deviations of the three lines for clothed men is somewhat smaller in a different position than that shown in Figure 13. Both lie in common area shown in the heavily cross-hatched area in the same figure, and its center lies at temperature of 97.1°F and a ratio of 1.35. This implies that the heat loss through the lungs is 26% of the metabolic rate, so if Burton's estimate of 25% is accepted it is well within the experimental error of the data taken from Robinson. (22)

The thermal acceptance ratio as has been defined herein is an empirical arrangement. The equations could be set up to derive it by theoretical means, but the equations are so complicated that it is difficult to draw any conclusions from them. The real test of such a system is whether or not it may be used easily and simply to give an index of climatic strain, and it should show a definite relation to the physiological variables within the system.

The relation between the thermal acceptance ratio and deep body temperature as taken from Robinson is data shown in Figure 15. When it is realized that this chart includes all of the data for men clothed and men wearing shorts and working at three different rates of activity in a number of different environmental conditions, the relation seems to be very good indeed. A sharp rise in internal temperature is observed when the body is under severe climatic stress.

Figure 16 shows the relationship between the heart rate and thermal acceptance ration, and again the scatter is no more than that usually found for heart rates.

Figure 17 shows the relationship between the internal conductance and the thermal acceptance ratio, and the scatter here is no more than is observed when a conductance is plotted against internal temperature.

The thermal acceptance of the atmosphere is something which may be measured on an instrument or which could be calculated accurately in the absence of outdoor radiation. When such radiation is present, it will be necessary to use Burton's (3) data for a rough estimate. The ratio for any activity may then be readily found by dividing the atmospheric acceptance by the metabolic rate.

The relation between the acceptance ratio and comfort may be found from the data on skin temperatures since the comfort range of skin temperature is known for low activity. No information is available, however, as to the range of comfortable temperatures for higher activities. It is possible to relate comfort to the conductance through the tissues and use this means of evaluating comfort in terms of thermal acceptance ratio. This and the correlation with other laboratories will be the subject of another report.

18

APPENDIX

EQUATION FOR SKIN TEMPERATURE AS A FUNCTION OF THERMAL ACCEPTANCE RATIO

Based on the data of Robinson's (22)

Clothing	Activity Kg. Cals.	Equation for T_s	Standard deviation of points about line	T_s at R= 1	Standard Deviation of line at R = 1
Jungle Suits	189	$T_s = 101.3-3.04R$	1.4	98.3	.35
Jungle Suits	125	$T_s = 98.9-1.49R$	1.5	97.4	.51
Jungle Suits	49	$T_s = 98.3-.51R$	1.1	97.8	.50
Shorts	188	$T_s = 99.4-2.25R$	2.0	97.2	.52
Shorts	130	$T_s = 98.2-1.25R$	1.3	97.0	.39
Shorts	46	$T_s = 97.1-.44R$	1.7	96.7	.70

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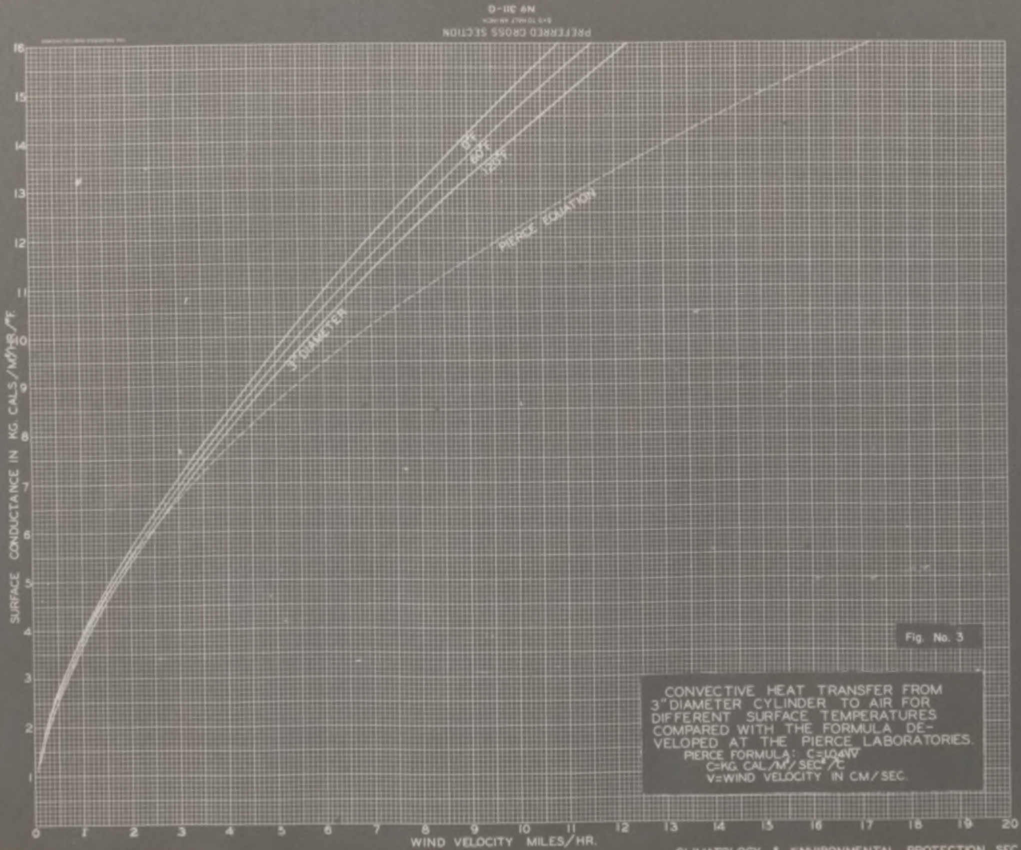

Fig. No. 3

CONVECTIVE HEAT TRANSFER FROM 3" DIAMETER CYLINDER TO AIR FOR DIFFERENT SURFACE TEMPERATURES COMPARED WITH THE FORMULA DEVELOPED AT THE PIERCE LABORATORIES.

PIERCE FORMULA: $C = 1.04\sqrt{V}$

C = KG. CAL/M²/SEC.²/°C

V = WIND VELOCITY IN CM/SEC.

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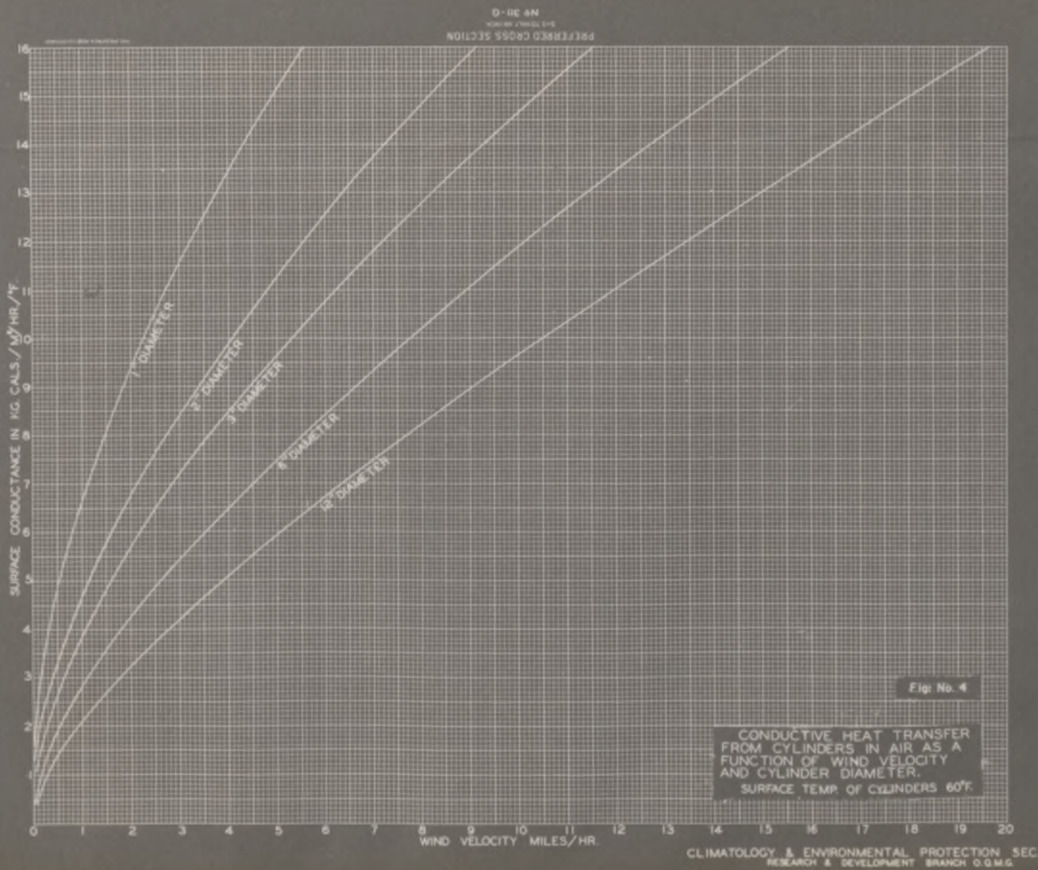
SURFACE CONDUCTANCE IN KG. CALS./M²/HR./°F.
WIND VELOCITY MILES/HR.
1" DIAMETER
2" DIAMETER
3" DIAMETER
6" DIAMETER
12" DIAMETER
Fig. No. 4
CONDUCTIVE HEAT TRANSFER FROM CYLINDERS IN AIR AS A FUNCTION OF WIND VELOCITY AND CYLINDER DIAMETER.
SURFACE TEMP. OF CYLINDERS 60°F.
CLIMATOLOGY & ENVIRONMENTAL PROTECTION SEC.
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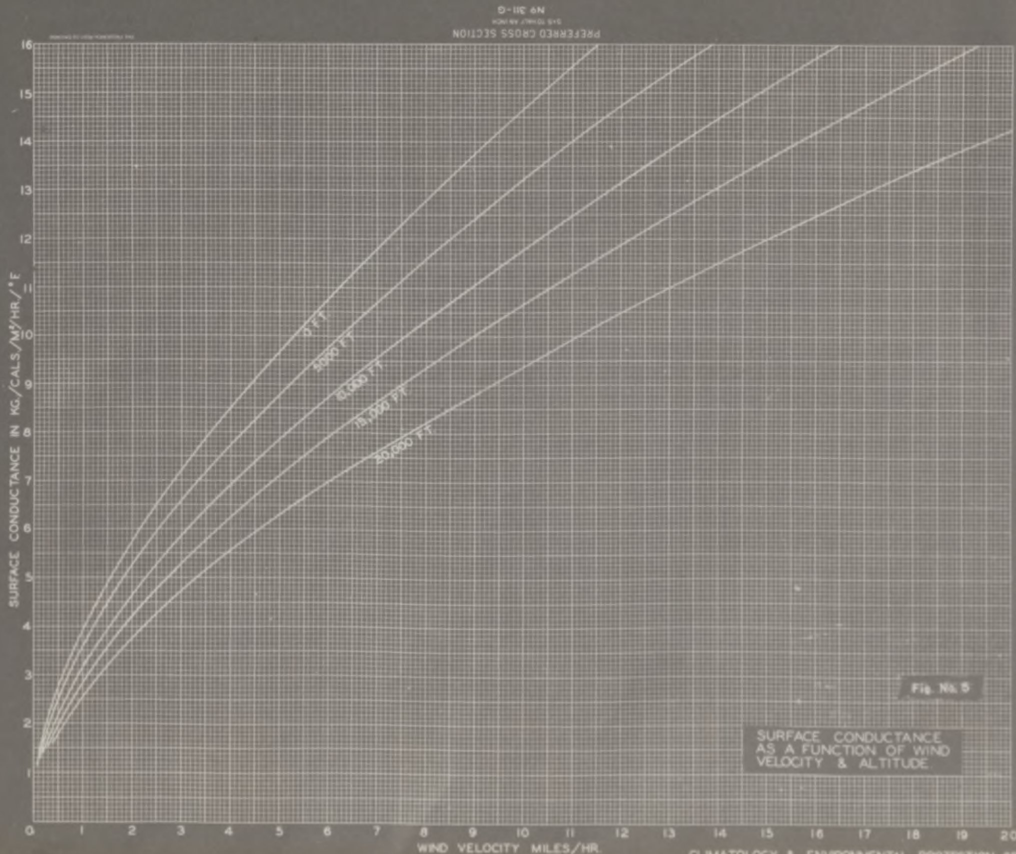

Fig. No. 5

SURFACE CONDUCTANCE AS A FUNCTION OF WIND VELOCITY & ALTITUDE

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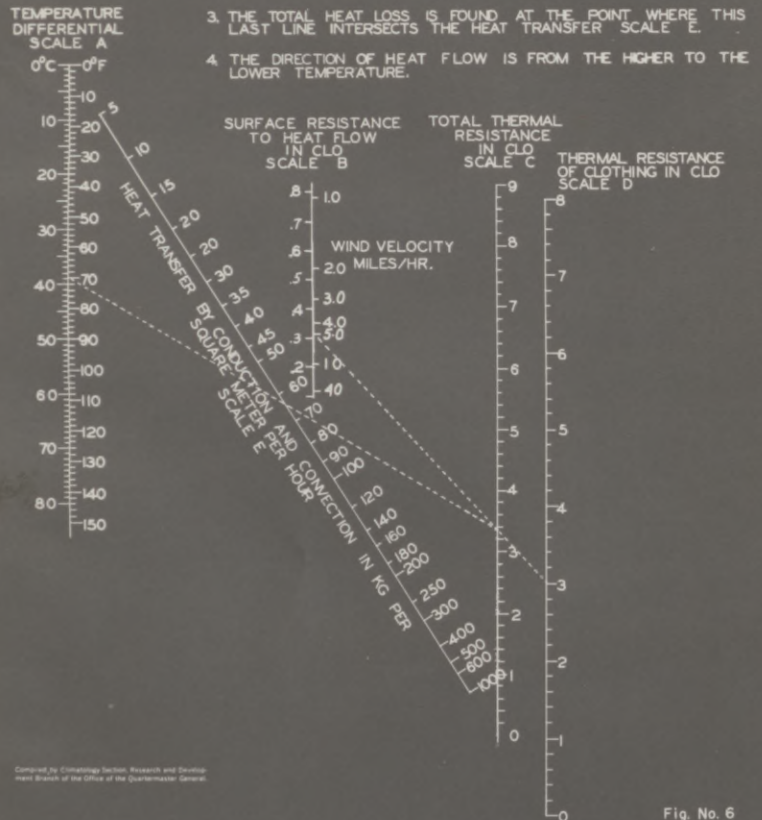
NOMOGRAM FOR CALCULATION OF CONDUCTIVE AND CONVECTIVE HEAT TRANSFER TO OR FROM THE HUMAN BODY

EXAMPLE: GIVEN:

SKIN TEMPERATURE	90°F
AIR TEMPERATURE	20°F
WIND VELOCITY	5 M.P.H.
CLOTHING	3 CLO

PROBLEM: TO FIND HEAT LOSS.

1. DRAW A STRAIGHT LINE FROM 5 ON THE WIND VELOCITY SCALE B TO 3 ON THE CLOTHING RESISTANCE SCALE D. THIS LINE CROSSES THE TOTAL RESISTANCE SCALE C AT 3.32.
2. DRAW A STRAIGHT LINE FROM 3.32 ON THE TOTAL RESISTANCE SCALE TO 70 ON THE TEMPERATURE DIFFERENTIAL SCALE A.
3. THE TOTAL HEAT LOSS IS FOUND AT THE POINT WHERE THIS LAST LINE INTERSECTS THE HEAT TRANSFER SCALE E.
4. THE DIRECTION OF HEAT FLOW IS FROM THE HIGHER TO THE LOWER TEMPERATURE.



Compiled by Climatology Section, Research and Development Branch of the Office of the Quartermaster General.

Fig. No. 6

NOMOGRAM FOR THE CALCULATION OF HEAT TRANSFER FROM THE HUMAN BODY BY CONDUCTION, CONVECTION, AND RADIATION WHEN THESE FACTORS CAN BE EXPRESSED AS RESISTANCES

EXAMPLE: GIVEN: SKIN TEMPERATURE 90°F.
AIR & SURROUNDING TEMPERATURE 20°F.
WIND VELOCITY 5 M.P.H.
CLOTHING 3 CLO

PROBLEM: TO FIND HEAT LOSS.

1. DRAW A STRAIGHT LINE FROM 5 ON THE WIND VELOCITY SCALE B TO 3 ON THE CLOTHING RESISTANCE SCALE D. THIS LINE CROSSES THE TOTAL RESISTANCE SCALE C AT
2. DRAW A STRAIGHT LINE FROM   ON THE TOTAL RESISTANCE SCALE TO 70 ON THE TEMPERATURE DIFFERENTIAL SCALE A
3. THE TOTAL HEAT LOSS IS FOUND AT THE POINT WHERE THIS LAST LINE INTERSECTS THE HEAT TRANSFER SCALE E.
4. THE DIRECTION OF HEAT FLOW IS FROM THE HIGHER TO THE LOWER TEMPERATURE.

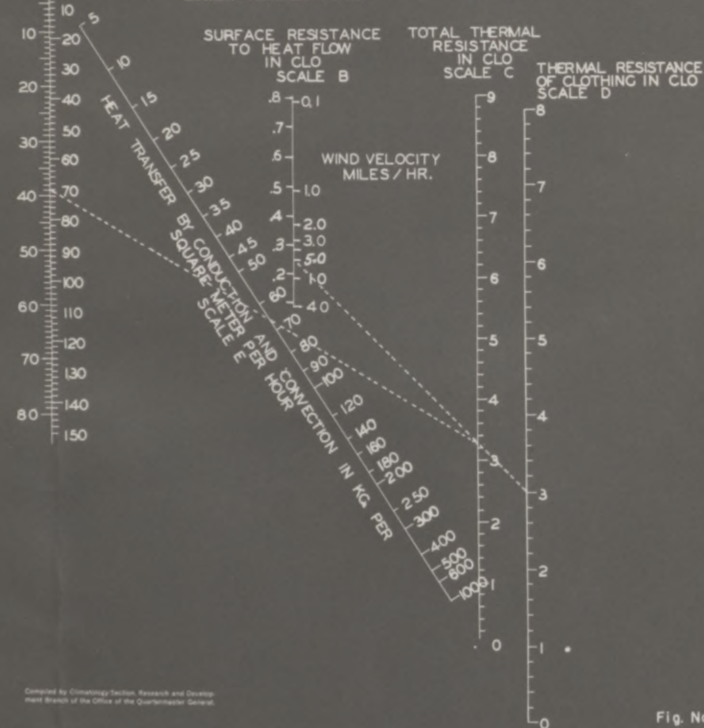


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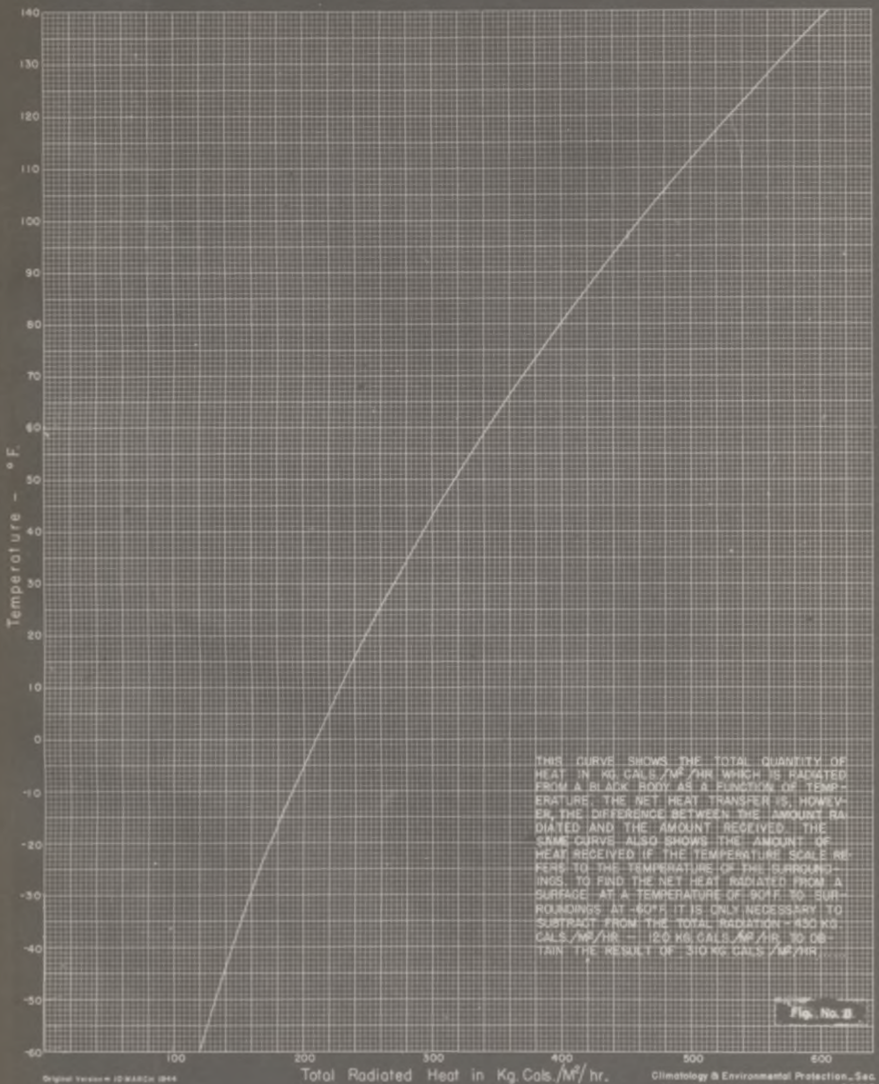
Fig. No. 7

RADIATION



Original Version - 10 MARCH 1944
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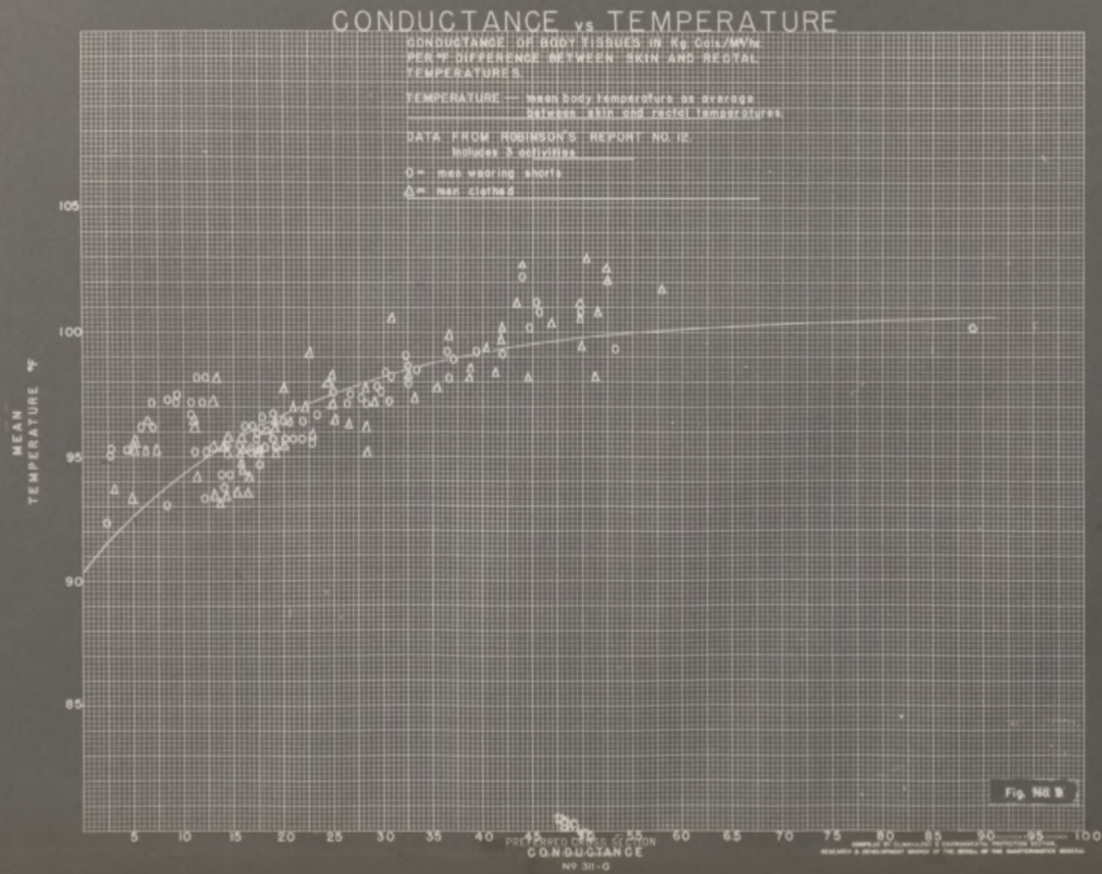
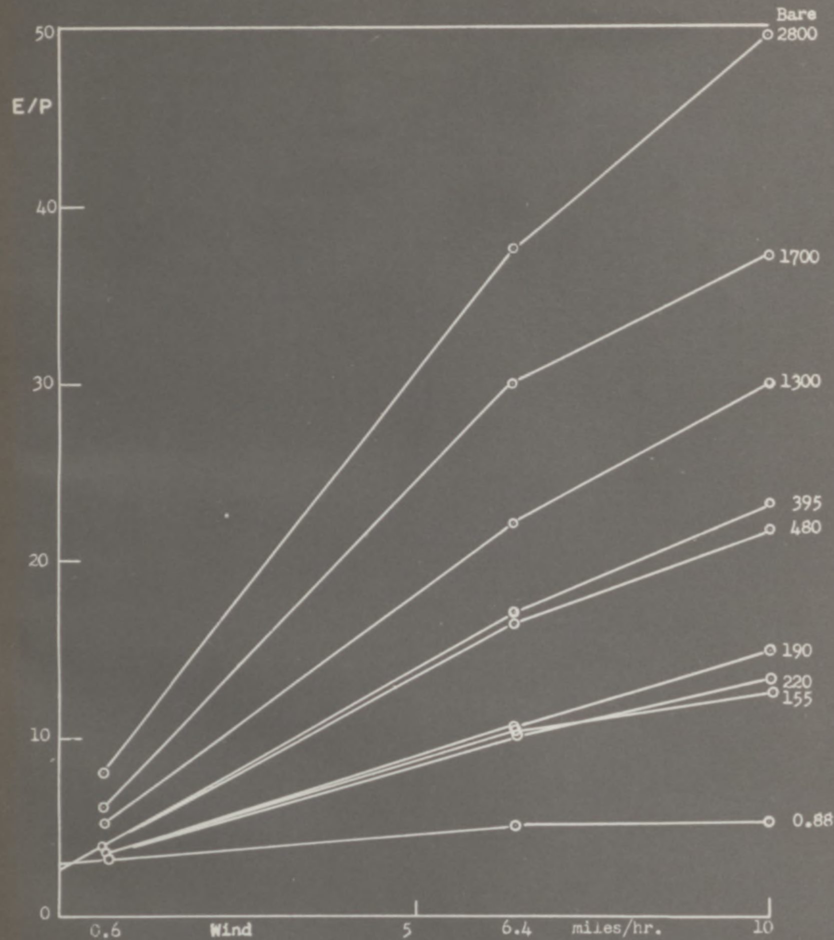
Research & Development Branch — O.Q.M.G.

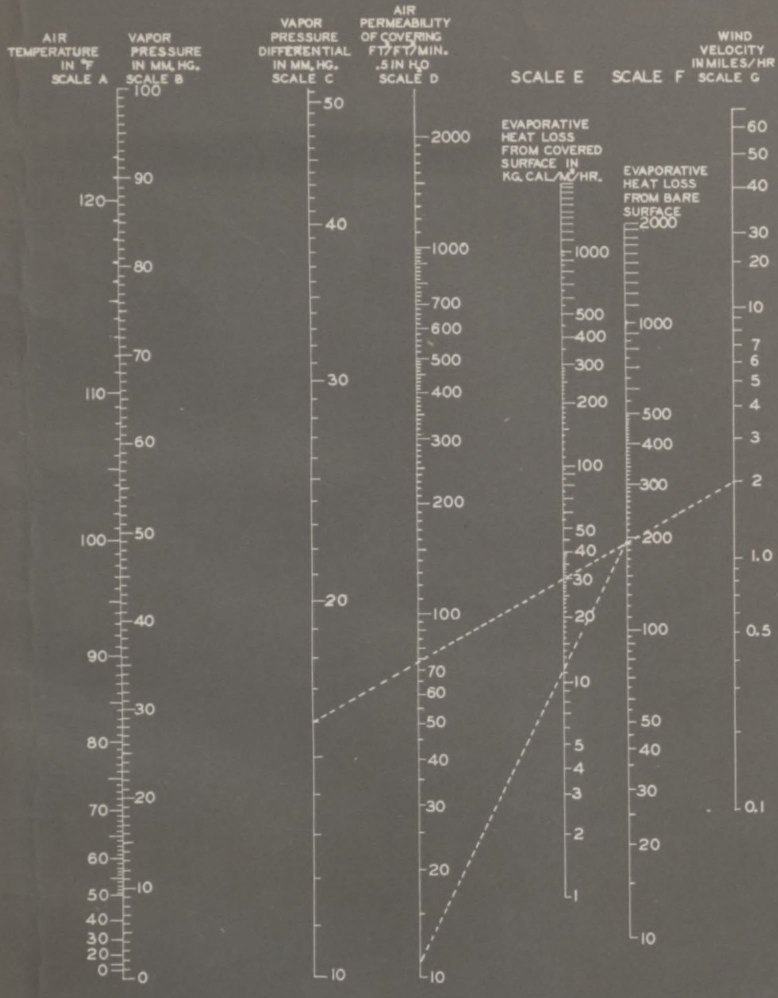

CONDUCTANCE vs TEMPERATURE
CONDUCTANCE OF BODY TISSUES IN Kg Cals/M²/hr
PER °F DIFFERENCE BETWEEN SKIN AND RECTAL
TEMPERATURES.
TEMPERATURE — mean body temperature as average
between skin and rectal temperatures.
DATA FROM ROBINSON'S REPORT NO. 12.
Includes 3 activities
O = men wearing shorts
Δ = men clothed
MEAN
TEMPERATURE °F
105
100
95
90
85
5
10
15
20
25
30
35
40
45
50
55
60
65
70
75
80
85
90
95
100
PREFERRED CROSS SECTION
CONDUCTANCE
Nº 311-G



Relationship of evaporation rate to wind velocity, for fabrics having the air permeabilities shown at the ends of the lines. E/P = Kg.cal/M^2 per mm. vapor pressure difference. Air permeability = ft^3/ft^2 min at pressure = 0.5 inch water.

Compiled by Climatology Section, Research and Development Branch of the Office of the Quartermaster General.

Fig. No. 10

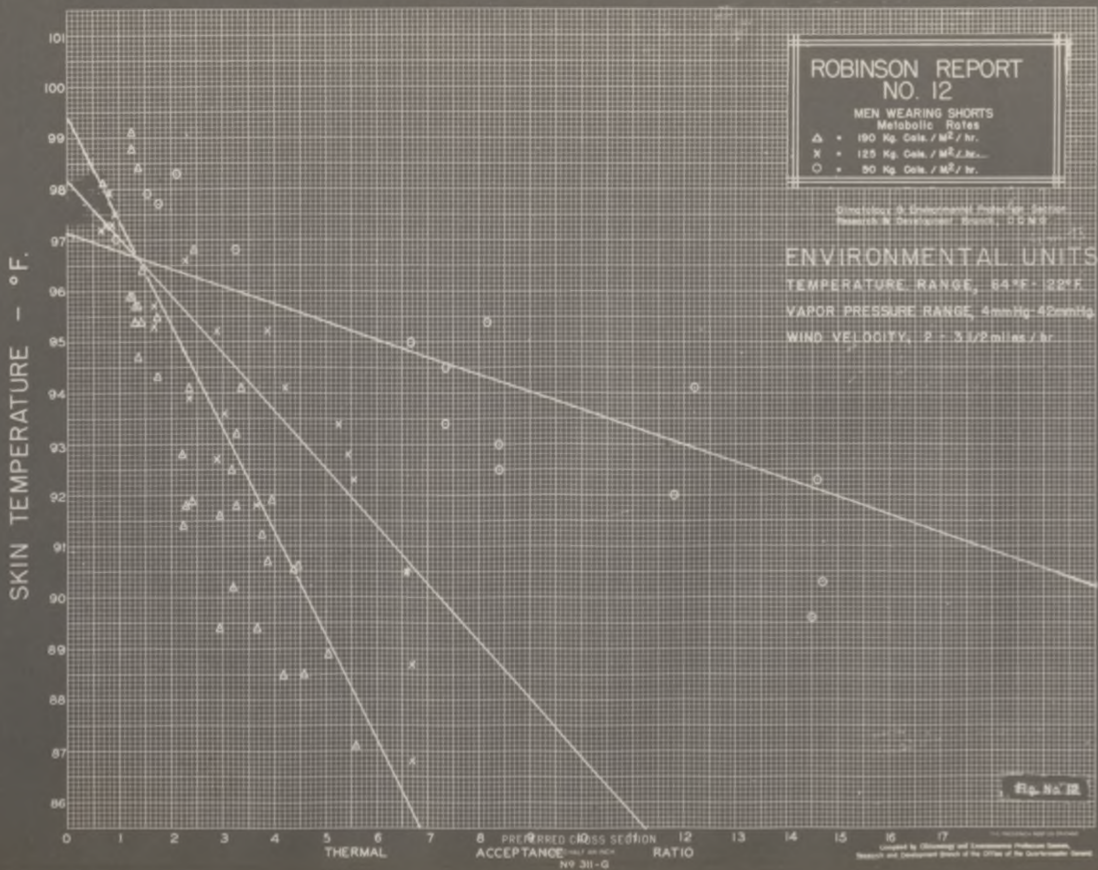


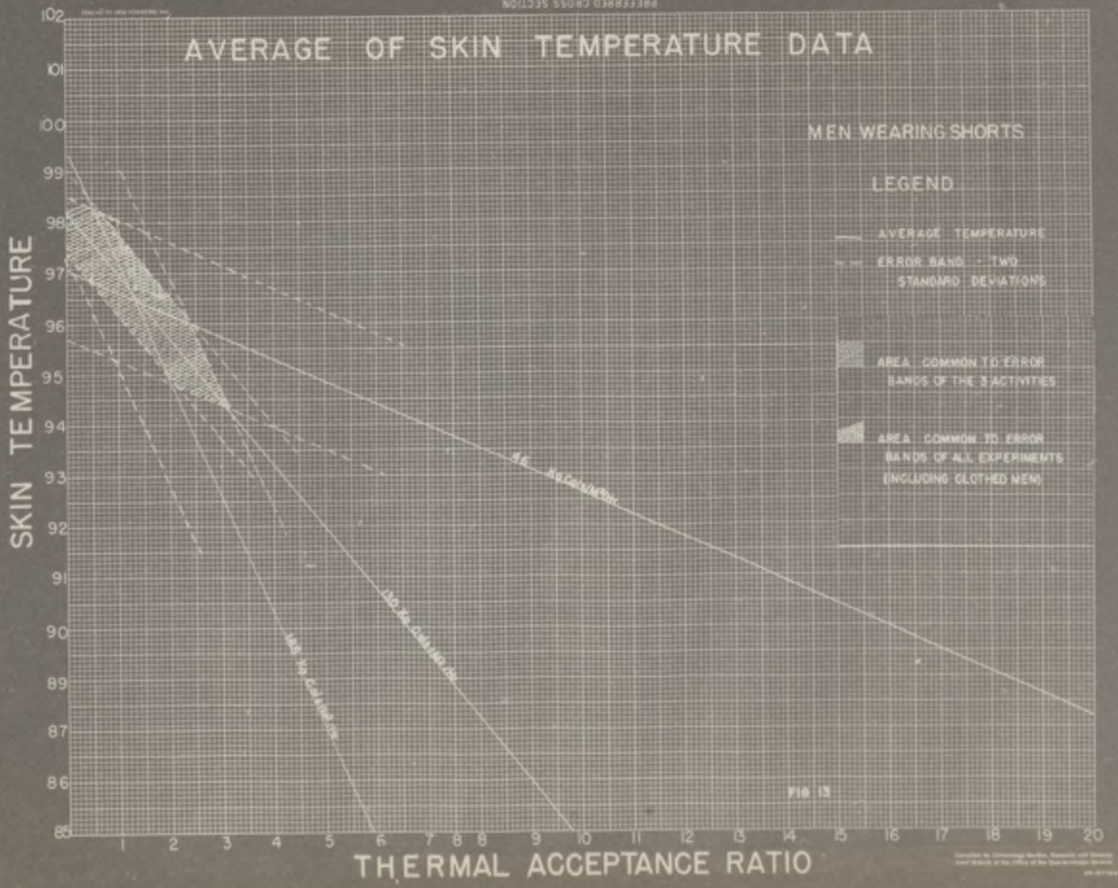
NOMOGRAM FOR CALCULATION OF EVAPORATIVE HEAT TRANSFER FROM THE HUMAN BODY

BASED ON THE EQUATION $E \backsim V^{0.6}[F/2800]^{1/2}$

Compiled by Climatology Section, Research and Development Branch of the Office of the Quartermaster General.

Fig. No. 11


SKIN TEMPERATURE - °F.
ROBINSON REPORT
NO. 12
MEN WEARING SHORTS
Metabolic Rates
Δ = 190 Kg. Cals. / M²/ hr.
X = 125 Kg. Cals. / M²/ hr.
O = 50 Kg. Cals. / M²/ hr.
ENVIRONMENTAL UNITS
TEMPERATURE RANGE, 84°F - 122°F
VAPOR PRESSURE RANGE, 4mmHg - 42mmHg
WIND VELOCITY, 2 - 3 1/2 miles / hr
THERMAL ACCEPTANCE RATIO
Fig. No 12


AVERAGE OF SKIN TEMPERATURE DATA
MEN WEARING SHORTS
LEGEND
AVERAGE TEMPERATURE
ERROR BAND - TWO STANDARD DEVIATIONS
AREA COMMON TO ERROR BANDS OF THE 3 ACTIVITIES
AREA COMMON TO ERROR BANDS OF ALL EXPERIMENTS (INCLUDING CLOTHED MEN)
SKIN TEMPERATURE
THERMAL ACCEPTANCE RATIO
85
86
87
89
90
91
92
93
94
95
96
97
98
99
100
101
102
1
2
3
4
5
6
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18
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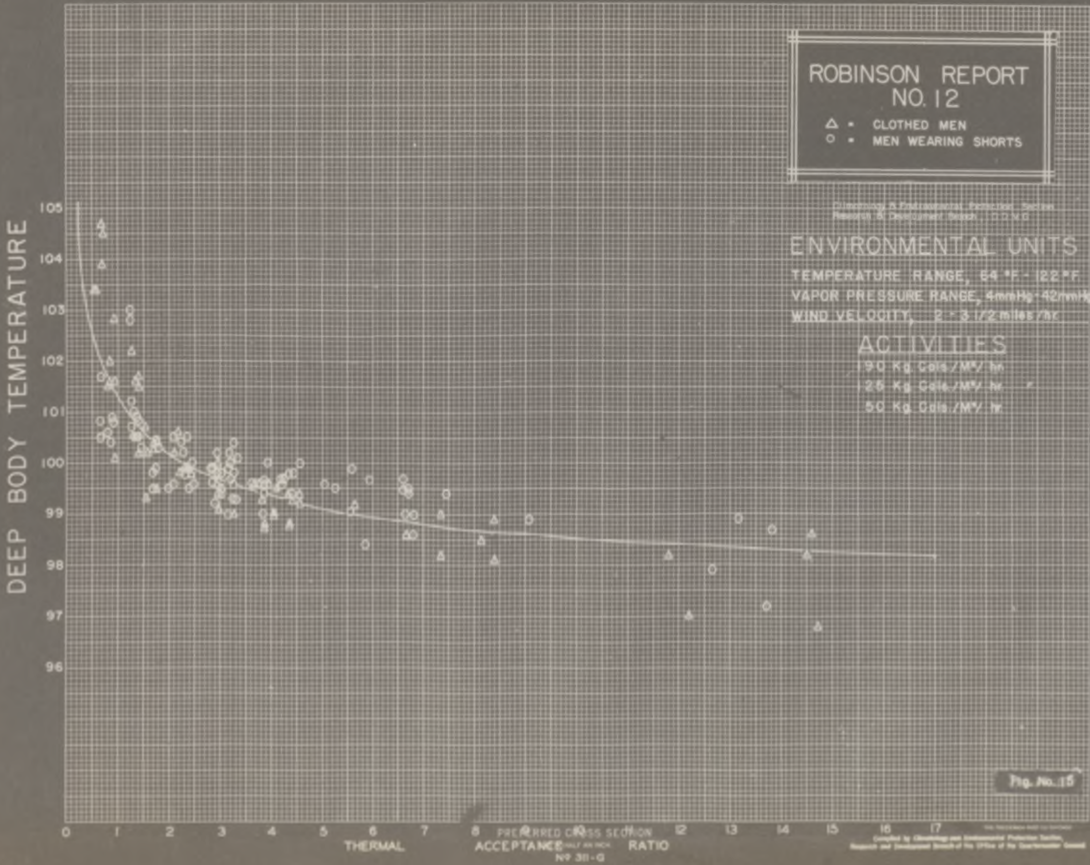
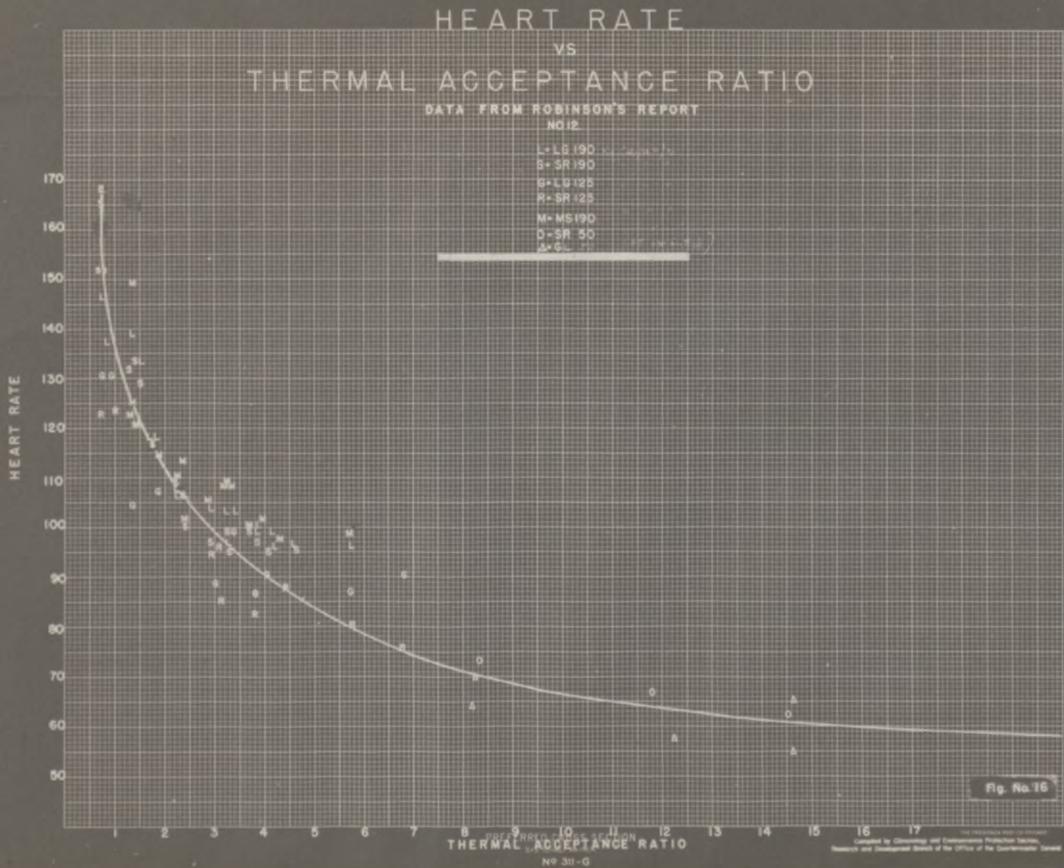
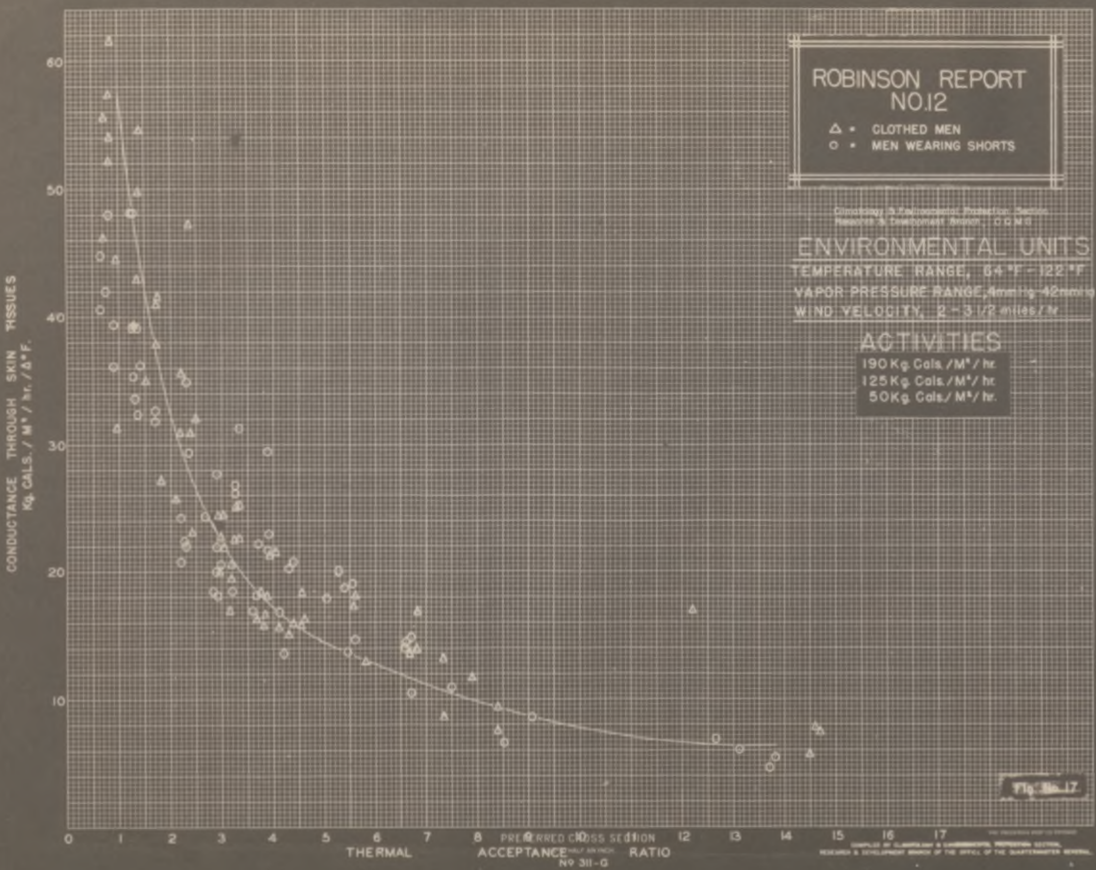
FIG 13


ROBINSON REPORT
NO. 12
△ - CLOTHED MEN
○ - MEN WEARING SHORTS
ENVIRONMENTAL UNITS
TEMPERATURE RANGE, 64 °F - 122 °F
VAPOR PRESSURE RANGE, 4mmHg - 42mmHg
WIND VELOCITY, 2 - 3 1/2 miles/hr.
ACTIVITIES
90 Kg Cals./M²/hr.
25 Kg Cals./M²/hr.
50 Kg Cals./M²/hr.
DEEP BODY TEMPERATURE
105
104
103
102
101
100
99
98
97
96
0
1
2
3
4
5
6
7
8
12
13
14
15
16
17
THERMAL ACCEPTANCE RATIO
PREFERRED CROSS SECTION
Nº 311-G
Fig. No. 15


HEART RATE
VS
THERMAL ACCEPTANCE RATIO
DATA FROM ROBINSON'S REPORT
NO 12
L-LG 190
S-SR 190
G-LG 125
R-SR 125
M-MS 190
D-SR 50
HEART RATE
THERMAL ACCEPTANCE RATIO
Nº 311-G
Compiled by Climatology and Environmental Protection Section,
Research and Development Branch of the Office of the Quartermaster General
Fig. No. 16



ROBINSON REPORT
NO.12
△ - CLOTHED MEN
○ - MEN WEARING SHORTS
ENVIRONMENTAL UNITS
TEMPERATURE RANGE, 64 °F - 122 °F
VAPOR PRESSURE RANGE, 4mmHg-42mmHg
WIND VELOCITY, 2 - 3 1/2 miles/hr
ACTIVITIES
190 Kg. Cals./M²/hr.
125 Kg. Cals./M²/hr.
50 Kg. Cals./M²/hr.
CONDUCTANCE THROUGH SKIN TISSUES
Kg. CALS. / M² / hr. / Δ°F.
THERMAL ACCEPTANCE RATIO
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17
10 20 30 40 50 60

Fig. No. 17