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AN EFFECTIVE TEMPERATURE SCALE BASED ON A SIMPLE MODEL OF HUMAN PHYSIOLOGICAL REGULATORY RESPONSE

The purpose of the present paper is to develop an environmental temperature scale based on our current knowledge of the physiology of heat regulation as it applies to comfort, temperature sensation, and health. We will construct this scale by using first the heat exchange equations during the passive state as a rational starting basis and by introducing then the effect of known physiological regulatory controls. The principles to be described may be applied to many levels of activities, to various air movements, and to radiant heating and cooling. However, our present discussion will deal primarily with normally clothed sedentary human subjects in a uniformly heated and normally ventilated environment. As a numerical index, the new temperature scale will be defined in terms of dry bulb and normal humidity and will be comparable to temperatures of *natural* environments, which one generally experiences in temperate climates.

Physiological Bases for a Temperature Scale

The first single temperature scale, which was used to measure the thermal comfort of the environment, was developed by Houghton and Yaglou[1] for ASH&VE in 1923. By a series of carefully chosen experimental conditions they were able to predict loci of constant temperature sensation expressed in terms of dry bulb and humidity. After almost 50 years this empirical psychophysical temperature scale is still in use the world over. This scale has shown the importance of humidity and dry bulb in judging comfort and heat stress and has been used as a temperature standard for working conditions in many occupations.[2,3] In later years Yaglou[4] recognized that his scale perhaps may have over-exaggerated the effect of humidity towards the lower temperatures. Minard[5] has shown the greater importance of wet bulb or dew point temperature toward the heat tolerance levels. Nevertheless there are many who still accept the older scale as a reasonable and logical estimate of environmental temperature stress for normally clothed sedentary persons.

Since the late 1930's there has been a continuing effort to rationalize sensory observations of comfort and temperature with the temperatures that occur simultaneously within the body and on the skin surface, with the various regulatory processes that result in vasoconstriction and vasodilation of the vascular system within the skin layer, and with the secretion of sweat necessary for evaporative cooling. The general nature of these processes has already been covered in the ASHRAE literature. Here the role played by this major physiological factor may be summarized briefly as follows:

Internal (or Core) Body Temperature

The experiments of Chatonnet and Cabanac[6] have shown for sedentary persons in a water bath that core temperature is a good index of thermal discomfort and that this sensation may be quite independent of skin temperature. The same observation in a calorimetry has been made by Benzinger.[7] During the exercise the same degree rise in core temperature does not cause necessarily the same discomfort as observed for sedentary conditions.

Skin Temperature

Skin temperature has long been recognized as a major factor in judging the temperature sensation caused by the environment. In cool or cold environments it also affects thermal comfort.[8,9] In both warmth and cold man's temperature sense is generally correlated with skin temperature and is

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apparently independent of his activity.[10] The distribution of skin temperature over the body surface is also a major factor in the cold;[11] the greater the uniformity the greater the comfort; the less, more discomfort. In the heat the sense of discomfort or unpleasantness, in contrast, is less dependent on skin temperature and more on core temperature or those central neural processes associated with the regulatory drive.[12,10] The same skin temperature may correlate with a warmer or colder temperature sensation than normal when the body temperature is lower or higher respectively than normal.[6]

Vasoconstriction and Vasodilation

Vascular control of blood flow to and from the skin surface is a method by which the body can change the flow of heat from its central core to the environment. Although this process is not as effective as shivering would be in the cold or as sweating in the heat, it can cause significant changes in man's sensation of well-being.[8] Vasoconstriction is usually associated with a sense of cold; vasodilation, which always occurs during regulatory sweating, may cause an increased sense of warmth. Without sweating, vasodilation may cause a sense of comfort or well-being although skin temperature may be well below the temperature threshold expected for a neutral sensation.

Sweating

Man's best protection against heat is his ability to use the evaporative cooling caused by his sweating. Sweating is caused by temperature stimuli from both the skin and core; there are both local controls and central controls.[13,14] Sweating *per se* is not an uncomfortable process as long as moisture can evaporate freely from the skin surface. Discomfort occurs, when the same rate of sweating requires a larger wetted surface on the skin from which it must evaporate. Sweating at very high levels is usually accompanied by active vasodilation, which in turn may cause swelling of the extremities, skin irritation, headaches and throbbing due to increased blood flow and heart action.

The Skin Surface

The skin surface is the boundary from which the human body exchanges heat with the environment by radiation, convection and evaporation. The heat of metabolism reaches this boundary surface by conduction and by blood flow. Secretion of perspiration on the boundary surface supports the evaporative cooling. Skin temperature and skin wettedness are the two principal physical properties of this boundary surface and are the *resultant* of both the various internal regulatory processes and the external thermal stress caused by the environment.

In the following section we will describe in familiar physical terms a model that contains the many physiologically dependent and independent variables described above and combine them to predict the physiology that occurs during a thermal state of quasi-equilibrium after a fixed exposure period to any various environmental condition.

THEORETICAL BASES

The Passive System

Part 1 – Skin to the Environment

The classic heat balance equation describing the heat gained from and lost to the environment may be written

$$S = M - E + R + C - W \quad \text{energy/time} \quad , \qquad (1)$$

where S = rate of heating (+) or cooling (–) by the body,
M = net rate of metabolic heat production,
E = total evaporative heat loss,
R = heat gained (+) or lost (–) by radiation,
C = heat gained (+) or lost (–) by convection,
and W = work accomplished.

In Eq (1) the conventional unit for heat exchange used by physiologists is the watt.[15] The corresponding English unit is Btuh. Since heat transfer coefficients will be involved in terms relating the heat exchange from the skin surface with the environment, the above terms will be described per unit area of the body surface as measured by DuBois.[16] For the remainder of this paper the units of choice will be W/sq m or Btu/(hr)(sq ft).

Metabolic rate M is proportional to the rate of O_2 consumption, which may be measured directly. E may be measured directly by observing the rate of body weight loss on a sensitive balance. These are well known procedures in partitional calorimetry.[17,18]

The total evaporative heat loss is divided into three parts; thus

$$E = E_{res} + E_{diff} + E_{rsw}, \qquad (2)$$

where E_{res} = heat of vaporized moisture from the lungs during respiration,
E_{diff} = heat of vaporized water diffusing through the skin layer,
and E_{rsw} = heat of vaporized sweat necessary for the regulation of body temperature.

In Eq (2) above the sum, $E_{res} + E_{diff}$, is known as the "insensible" heat loss from the body; the component E_{rsw} as the "sensible" loss.

In general E_{res} is directly proportional to the vapor pressure gradient from the lungs to the ambient air and to the ventilation rate of the lungs. The latter term is proportional to the metabolic rate itself. Fanger[19] has developed the following relation for E_{res}, based on data available in physiological literature;

$$E_{res} = 0.0023\, M\, [44 - \phi_a P_a], \quad \text{in W/sq m} \qquad (3)$$

where 44 mm of Hg = the saturated vapor pressure for an average lung temperature of 35.5 C (96 F),
ϕ_a = relative humidity as a fraction,
and P_a = the saturated vapor pressure for the dry bulb or air temperature (T_a) of the environment in mm of Hg.

Eq (3) is useful for resting to moderate exercise.

The maximum evaporative heat loss E_{max} from the body surface has been shown to be[12,20]

$$E_{max} = \kappa\, h_c [P_{sk} - \phi_a P_a]\, F_{pcl} \quad \text{in W/sq m} \qquad (4)$$

where κ = the Lewis relation and equals 2.2 C/mmHg (or 31 F/in Hg) at sea level,
h_c = convective heat transfer coefficient in W/(sq m)(C)

P_{sk} = the saturated vapor pressure at mean skin temperature T_{sk} in mm (or in) of Hg,

and F_{pcl} = permeation efficiency factor for water vapor evaporated from the skin surface through clothing to the ambient air.[21]

In general, E_{max} is a direct measure of the evaporative power of the environment for moisture or sweat accumulated on the body surface.

The evaporative loss E_{sk} from the skin surface may be observed experimentally by subtracting E_{res} from the value of E, found by measuring the rate of weight loss. It is also given by

$$E_{sk} = E_{diff} + E_{rsw} \,. \tag{5}$$

The ratio E_{sk}/E_{max} is a measure of the average wettedness (w) of the body skin surface.[22] Its minimum value occurs when the skin evaporative loss is insensible. When E_{sk} is defined as the evaporative heat loss necessary for the regulation of body temperature (i.e. S=0), the ratio $E_{sk}/E_{max} \times 100$ has been used by Belding and Hatch[23] as an index of environmental heat stress.

Brebner *et al.*[24] have shown E_{diff}, when $E_{rsw} = 0$, to be proportional to evaporative power of the environment E_{max}. Using their data

$$w_{diff} = E_{diff}/E_{max} = 0.06 \qquad \text{(N.D.)} \tag{6}$$

The value of 0.06 for w_{diff} represents the normal dampness factor for human skin without sweating. This value may drop as low as 0.04 when dehydration of the skin from exposure to cold and lower humidities causes a change in its diffusive characteristics for body water.[25]

In warm environments, as the sweat glands become successively active for the regulation of body temperature and as this secretion spreads as an evaporating thin film over the body surface, the proportion of skin areas with insensible perspiration becomes less and those with wet surfaces due to sweating become greater. E_{diff} and E_{rsw} never occur on the same area of the skin at the same time. At any time w_{rsw} equals E_{rsw}/E_{max}. When the surface is fully wet, $w = w_{rsw} = 1$. When $w_{rsw} = 0$, $w = w_{diff} = 0.06$. These two limits, as well as the intermediate, conditions are described when the total loss from the skin surface E_{sk} is written as follows:

$$E_{sk} = (0.06 + 0.94\, w_{rsw})\, E_{max} \tag{7}$$

For the present analysis we will consider the environment to be at a uniform temperature, T_a. The dry heat exchange from the skin surface is described by

$$(R + C) = h(T_{sk} - T_a)\, F_{cl} \tag{8}$$

where h = the combined heat transfer coefficient and is the sum of the linear radiation exchange coefficient h_r and the applicable convective heat transfer coefficient h_c in W/(sq m)(C) or Btu/(hr)(sq ft)(F),

and F_{cl} = a factor that measures the efficiency for the passage of dry heat from the skin surface at T_{sk} through the clothing to the environment at T_a.

F_{cl} and F_{pcl} are analogous factors for heat transfer by convection and for mass transfer by water vapor respectively and, as concepts, were originally proposed by Burton and Edholm.[26] Both are a function of the clothing insulation I_{cl} in clo units as well as the coefficients h and h_c respectively[21].

In a uniform environment we may now write the complete heat balance equation for a subject not doing external work (W)

$$\begin{aligned} S = M\,[1 - 0.0023(44 - \phi_a P_a)] \\ - 2.2\, h_c\,(0.06 + 0.94\, w_{rsw})\,[P_{sk} - \phi_a P_a]\, F_{pcl} \\ - (h_r + h_c)(T_{sk} - T_a)\, F_{cl} \end{aligned} \tag{9}$$

Alternatively Eq (9) may be rewritten

$$\begin{aligned} S = M\,[1 - \mu - 0.0023\,(44 - P_{dew})] - 2.2 w\, h_c\,(P_{sk} - P_{dew}) \\ F_{pcl} - h(T_{sk} - T_a)\, F_{cl} \end{aligned} \tag{10}$$

where the mechanical efficiency μ is equal to W/M and P_{dew} is the saturated vapor pressure at dew point, T_{dew}.

The reader will recognize the first term on the right of Eqs (9) or (10) as the net heat produced by the body which is lost through the skin surface; the second is the total evaporative heat loss from the skin surface; and the third is the dry heat exchange. The units in use may be either W/sq m, W/(sq m)(C), mm Hg; or Btu/(hr)(sq ft), Btu/(hr)(sq ft)(F), or in of Hg.

PART 2 – FOR CORE AND SKIN

The core and skin of the human body will be treated analytically as two concentric shells (Fig. 1); the skin is represented by a thin shell with mass m_{sk}; the body interior by

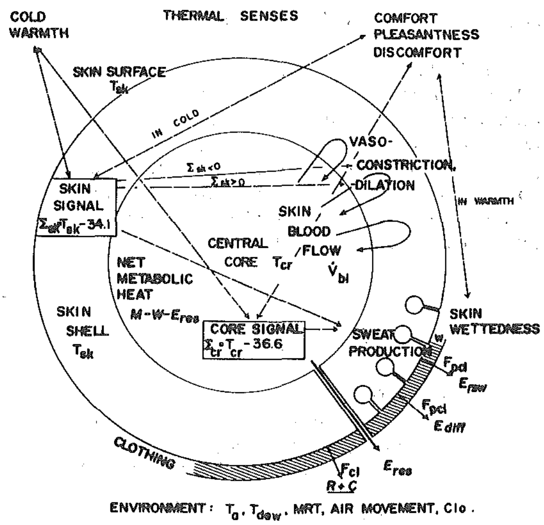

Fig. 1 A concentric shell model of man and his environment

a central core with mass m_{cr}; the total body mass m in kg will be $m_{sk} + m_{cr}$; the body surface area will be A, which will be equal in magnitude to the DuBois area (2.0 sq m) of a standard man (81.7 kg-weight and 1.77 m height). The core mass is considered as 78.3 kg and the skin shell as 3.4 kg. The SI-system[15] of units will be used in the following analysis.

The net heat flow to and from the skin shell is given by the relation

$$S_{sk} = K_{min}\,(T_{cr}-T_{sk}) + c_{bl}\,\dot{V}_{bl}\,(T_{cr}-T_{sk}) - E_{sk} - (R+C) \quad (11)$$

where S_{sk} = rate of heat storage in W/sq m,
c_{bl} = specific heat of blood in W(hr)/(kg)(C),
$\dot{V}_{bl}$ = rate of skin blood flow in liter/(hr)(sq m),
and K_{min} = minimum heat conductance of skin tissue W/(sq m)(C).

The net heat flow to and from the core is given by

$$S_{cr} = (M-E_{res}-W) - K_{min}(T_{cr}-T_{sk}) - c_{bl}\dot{V}_{bl}(T_{cr}-T_{sk}). \quad (12)$$

It is clear to the reader that the total body heat storage S is given by

$$S = S_{sk} + S_{cr}, \quad \text{W/sq m} \quad (13)$$

as may be seen from Eqs (9) or (10) above.

The total thermal capacity of the skin shell and core are

$$c'_{sk} = 0.97\, m_{sk}, \quad \text{W(hr)/C} \quad (14)$$

and

$$c'_{cr} = 0.97\, m_{cr}, \quad \text{W(hr)/C} \quad (15)$$

where the primes refer to the entire shell or core and 0.97 is the specific heat of the body in W(hr)/(kg)(C).

The rate of change in skin (shell) temperature T_{sk} and central core temperature T_{cr} are given by

$$\dot{T}_{sk} = S_{sk}A/c'_{sk}, \quad \text{C/hr} \quad (16)$$

and

$$\dot{T}_{cr} = S_{cr}A/c'_{cr}. \quad \text{C/hr} \quad (17)$$

In Eqs (16) and (17) the cooling and warming is considered as Newtonian for the core and shell and assume these are uniformly at temperature T_{sk} and T_{cr} respectively. We also assume that the same body surface area A applies to the skin surface and core surface. If the skin and body are at 34.1 C and 36.6 C respectively on initial exposure to an environment described by T_a and ϕ_a, then the values of T_{sk} and T_{cr} at any time are given by

$$T_{sk} = 34.1 + \int_0^t \dot{T}_{sk}\,dt, \quad (16a)$$

and

$$T_{cr} = 36.6 + \int_0^t \dot{T}_{cr}\,dt. \quad (17a)$$

The Controlling System

As implied in our physiological considerations above, we will assume that the temperature signals Σ from the skin shell and the central core are given by the two relations:

$$\Sigma_{sk} = T_{sk} - 34.1 \quad (18)$$

$$\Sigma_{cr} = T_{cr} - 36.6 \quad (19)$$

The values 34.1, and 36.6 have been observed[27] as the average temperature of the skin and core, when there is minimal regulatory effort in maintaining body temperature either by any vascular effort or by sweating. When these temperatures occur simultaneously during rest, the body is in a state of "physiological thermal neutrality."

When Σ_{sk} is negative, the skin senses "cold." When Σ_{sk} is positive, the skin senses "warmth." Likewise, when Σ_{cr} is negative, the core senses "cold" and positive the core senses "warmth." A "cold" signal from the skin primarily governs "vasoconstriction" in the vascular bed of the skin and thus reduces the blood flow from core to skin. A warm signal from the skin, as will be seen later, plays a more important role in body temperature regulation by governing sweating than by governing vasodilation. A warm signal from the core, will cause dilation in the vascular bed and evoke sweating. The corresponding cold signal from the core will cause vasoconstriction but not as rapidly or effectively as one from the skin. In a multicompartment model Stolwijk and Hardy[27] have estimated for each deg C drop for a cold Σ_{sk}, skin blood flow will encounter a proportional increase in resistance. For the hands and feet alone this resistance factor may be twice as great with each degree drop; for the trunk vasoconstriction may be negligible. For the core, each deg C rise will cause an increase in skin blood flow of 75 liter/(hr)(sq m) above a *normal* skin blood flow of 6.3 liter/(hr)(sq m), a value which occurs at rest during thermal neutrality. The above statements may be described by the following equation, which gives the skin blood flow $\dot{V}_{bl}$ at any time as:

$$\dot{V}_{bl} = (6.3 + 75\,\Sigma_{cr})/(1 - 0.5\,\Sigma_{sk}) \text{ in l/(hr)(sq m)} \quad (2$$

In Eq (20) when Σ_{cr} represents a cold signal (i.e. $T_{cr} < 36$ and/or when Σ_{sk} represents a warm signal (i.e. $T_{sk} < 34.1$), the numerical value of Σ in either case is considered as zero

The glands that produce the regulatory sweating $\dot{m}_{rsw}$ in g/(hr)(sq m) at the skin surface, necessary for temperature regulation by evaporation, are activated both by the core signal Σ_{cr} and by the product $(\Sigma_{sk})(\Sigma_{cr})$. The rate o sweat production may be written as:

$$m_{rsw} = 250\,\Sigma_{cr} + 100\,(\Sigma_{cr})(\Sigma_{sk}). \quad (2$$

The first term of Eq (21) has significance primarily during exercise; each degree change in core temperature (e.g. rect temperature) above 36.6 C has been observed by Saltin *et al.*[28] to cause an average increase in sweat secretion of 250 g/(hr)(sq m) (C). The second term has been shown by Hardy and Stolwijk[14,27] to describe the sweat drive durin rest; the factor, 100 g/(hr)(sq m) (C^2), represents the dual effect of a gain controller with an output described by the product $(\Sigma_{cr})(\Sigma_{sk})$. The double – Σ terms have less significance during exercise as T_{sk} falls below 34.1 C. Whenever Σ is negative (i.e. a cold signal), its value in Eq (21) is zero.

Bullard *et al.*[13] have recently shown that skin temperature can modify locally the production of sweat. This non dimensional control factor may be represented by a power function described by $2^{(T_{sk}-34.1)/3}$. Thus each 3 deg rise in T_{sk} above 34.1 C doubles the ease of sweat production; this may occur during exposure to radiant heat for examp A 3 deg drop in T_{sk} from 34.1 C will reduce the local swe production to a half; this drop occurs during exercise and

TABLE 1

STANDARD ENVIRONMENTAL PARAMETERS

Term	Units	Type of Activity					
		A	B	C	D	E	F
M	mets * (W/sq m)	1 (58.2)	2 (130.1)	1 (58.2)	4 (233)	4	5 (291)
h_r	W/(sq m)(C)	5.23	5.23	5.23	5.23	5.23	5.23
h_c	W/(sq m)(C)	2.91	4.30	2.91	6.8	10.00	5.37
h		8.14	9.53	8.14	12.03	15.23	10.60
I_{cl}	clo*	0.6**	0.6**	0	0.1#	0.1	0.1
μ		0	0	0	0	0	0.2

**The met unit*[31] *is equal to 50 kcal/(hr)(sq m); 58.2 W/sq m or 18.5 Btu/(hr)(sq ft); for an average sized man this unit corresponds approximately to 90 kcal/hr, 100 watts, or 400 Btuh. The clo*[31] *unit is 0.18 (C)/(sq m)(hr)/(kcal); 0.88 (F)/(sq ft)(hr)/(Btu); or 0.155 (C)/(sq m)/W.*

***Equivalent to KSU Standard Clothing.*[29]

#Indoor athletic clothing.

modifies the powerful control drive of sweat secretion caused by Σ_{cr}. The heat loss from regulatory sweating may now be written as;

$$E_{rsw} = 0.7\ \dot{m}_{rsw}\ [2^{(T_{sk}-34.1)/3}]\ , \qquad (22)$$

where 0.7 is the latent heat of sweat in W(hr)/g.

The equations of state describing the energy exchanges and temperatures of the shell-core model at any time are given by Eqs (9), (10), (12), (16) and (17). From the initial conditions that describe thermal neutrality it is possible to integrate the changes in skin and core temperature and the sweating caused by the controlling system (Eqs 18, 19, 20 and 22) and to predict all the physiological energy and temperature factors after any period exposure to any new environment described by T_a and humidity.

In a complex multiloop regulatory system, such as we use here, the coefficients used in Eqs (20) and (21) are not as significant in changing predictions of body temperatures as are the choice of the set points for T_{sk} and T_{cr} in Eqs (18) and (19). In contrast, the prediction of any environmental temperature for any energy exchange relationship or any value skin wettedness is not significantly changed by a small displacement 0.5 C (or 1 F) in any set point. The heat transfer coefficients introduced by the environment and the metabolic level primarily govern the pattern of loci of constant wettedness, of constant skin temperature or of constant core temperature in terms of dry bulb and humidity.

An annotated Fortran program incorporating the above equations, is given in the Appendix and is generally applicable to moderate levels of activity, to normal fabric clothing and to environmental conditions described by dry bulb temperature in range 5-45 C and by humidities down to 10%. The effect of radiant heating has not been included. There are seven independent variables in our model; namely (1) the metabolic rate; (2) the work accomplished; (3) the combined and (4) convective heat transfer coefficients, which both include the effect of air movement caused by both room ventilation and body activity; (5) the insulation of normal clothing used; (6) the dry bulb temperature; (7) the humidity, as measured by either ϕ_a, T_{wet}, or T_{dew}.

For these seven variables the principal physiological factors, predictable by our model, are average skin temperature T_{sk}, the core temperature T_{cr}, the regulatory sweating E_{rsw} and the corresponding skin wettedness w_{rsw}. Engineers interested in using this model can find a variety of sources in literature for evaluating variables (1) – (5).

Standard Conditions

Four types of general activity will be considered in the present paper:

A – Clothed and sedentary
B – Moderate activity
C – Unclothed and sedentary
D – 3 mph on treadmill
E – 3 mph free walking
F – Bicycle Ergometer (50 rpm)

The environmental parameters to be used for each are given in Table 1.

In Table 1, activity A occurs most probably for 90% of our current living conditions in the home and office. Activity C is the same sedentary level but unclothed. Activity B may be classed as a light physical effort and occurs most frequently in industries such as bakery, brewery, small machine work and also in house cleaning, domestic work, and washing by hand. It also corresponds to the moderate activity report by McNall *et al.*[29] Activities C and the following are of interest in heat tolerance and health studies. Activity D, E and F represent moderate exercise. For activity F the work-efficiency is 20% and is at approximately 40% of man's average maximal oxygen capacity. The values for h_c in Table 1 were measured directly by naphthalene sublimation.[30]

It is now possible to use our model to predict at the end of 1 hour exposure the equilibrium status for any combination of T_a or humidity. Fig. 2 for example indicates the predicted partitional calorimetry of a subject sitting and resting when clothed (Activity A). Five factors have been plotted for the temperature ranges 10-40 C or 50-105 F; T_{sk}, T_{cr}, $\Delta T_B/\Delta t$ (i.e. change in mean body temperature/hr), E_{rsw}, E_{ins},(i.e. $E_{res} + E_{diff}$), w_{rsw} and $\dot{V}_{bl}$ (skin blood

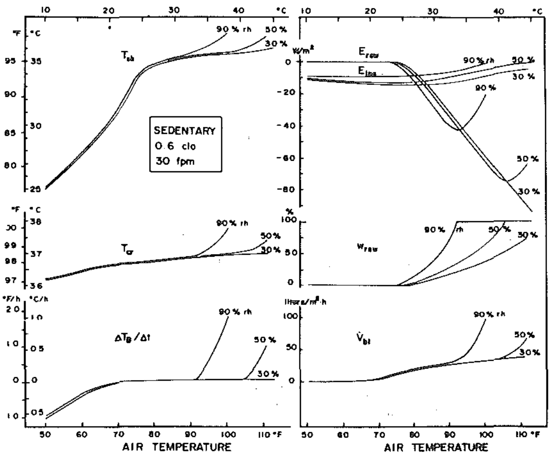

Fig. 2 Changes in various body temperatures, skin blood flow, evaporative cooling for a normal clothed man, predicted by our model and Fortran program in Appendix.

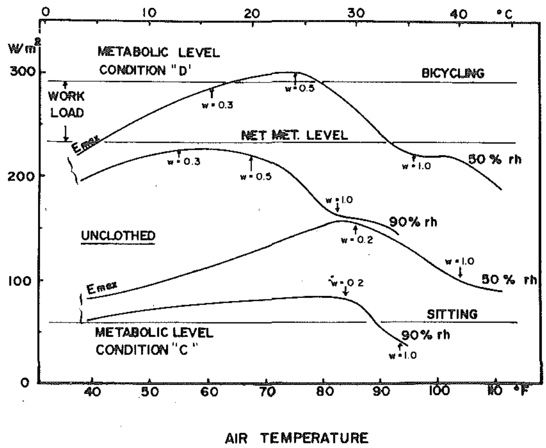

Fig. 3 Variations in E_{max} with increasing ambient temperature. The corresponding skin wettedness predicted by model has been shown for activities and humidity levels indicated.

flow). Regulatory sweat for both high and low humidity begins at 24 C (75.2 F) and increases steadily with increasing temperature. The rate of rise is slightly higher with increasing humidity. The skin temperature is also slightly higher with humidity, as air temperature increases. When skin wettedness reaches 100%, skin temperature, core temperature and skin blood flow all rise sharply and this leads to the sudden collapse of the subject. Above this maximum (w=1), the effective E_{rsw} steadily drops. The relationships in Fig. 2 are idealized in the sense that the assumption has been made that all evaporation takes place on the skin surface. As the predicted wettedness limit passes through 75-100% range, the true maximum evaporative loss may occur at lower temperatures because of evaporation of sweating in the clothing itself. The general pattern and principles outlined above still apply and represent realistic prediction for normal lightweight porous clothing.

During exercise and with increased body motion the ability to regulate body heat by evaporation is increased about 2 times over the sitting-resting levels. This fact is illustrated in Fig. 3 where the values of E_{max} for the resting and bicycling unclothed subjects at various dry bulbs and humidities are compared. Skin wettedness for various points along the E_{max} curves has been indicated. The magnitude of the net metabolic levels concerned are shown.

In studies of heat tolerance the physical factors that set the maximum wettedness limits are the net metabolism, clothing, air movement, and the dry and dew point temperatures. Fig. 4 demonstrates some of these inter-relationships on a T_{dew}-T_a plot. In the upper section of Fig. 4 for a constant metabolic rate of 1 met, the effect of various clothing insulation on the 100% wettedness limit is demonstrated. In all cases, the ambient air movement is held constant as conditions A and C in Table 1. Over the range 0-0.9 clo clothing has a small effect on the regulatory limit. In the lower section of Fig. 4 the net metabolic rate has been adjusted to a 4 met level. The limits for three types of exercise – free walking, treadmill walk, and bicycle ergometry – are indicated. When the environmental variables are held constant, the maximum wettedness limit lowers with increasing activity. Clothing increases the relative importance of the dew point temperature (and of wet bulb) in relation to the ambient temperature. Increasing air movement also increases the significance of dew point temperature over dry bulb.

Humid Operative Temperature (T_{oh})

Let us define humid operative temperature as the imaginary temperature at which the body will lose the same heat as he would by radiation, convection and evaporation in the

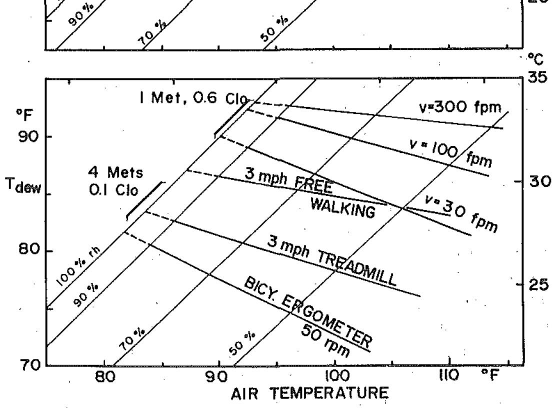

Fig. 4 The effect of clothing insulation, air movement, and exercise on the loci for maximum wettedness ($w = w_{rsw} = 1$)

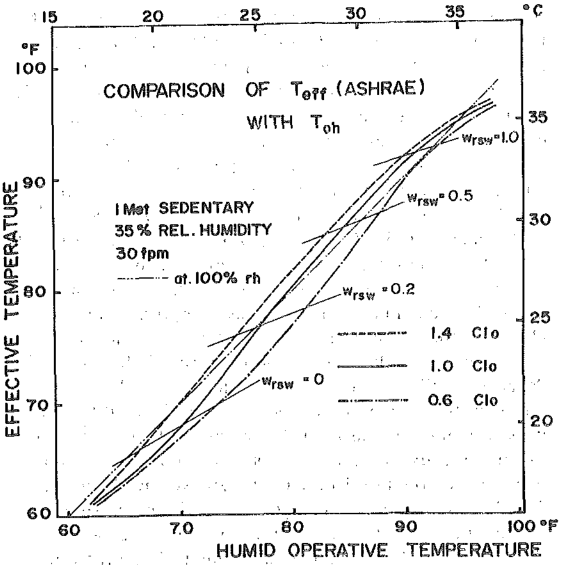

Fig. 5 A comparison of the predicted humid operative temperature with the current ASHRAE effective temperature scale for various clothing insulations

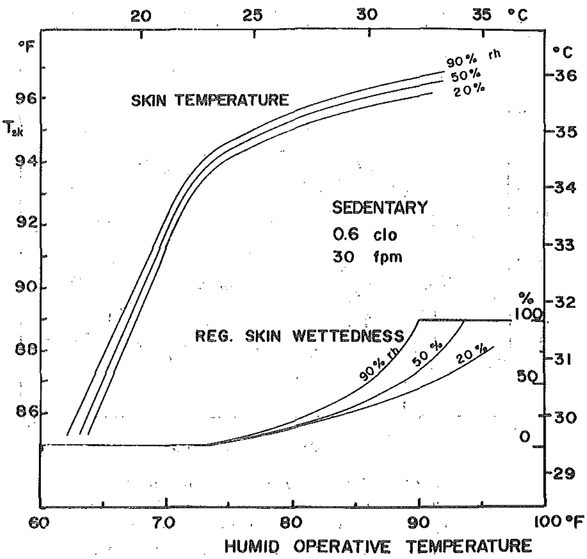

Fig. 6 The relationship between skin temperature, regulatory skin wettedness, and humid operative temperature as predicted by our model

actual environment. From Eq (10) the total heat loss from the skin surface H_{sk} may be written as

$$H_{sk} = h(T_{sk}-T_a)\,F_{cl} + 2.2\,w\,h_c\,(P_{sk}-P_{dew})F_{pcl}\,. \qquad (23)$$

Over the range 10 C-40 C (50 F-105 F) for our physiological model, the following relation is true,

$$P_{sk}-P_{dew} = 1.4\,(T_{sk}-T_{dew})\,. \qquad (24)$$

By combining Eqs (23) and (24), the equations defining T_{oh} in a uniform environment are

$$H_{sk} = A(T_{sk}-T_a) + B(T_{sk}-T_{dew})\,; \qquad (25)$$

where $A = h\,F_{cl}$, (25a)

$$B = 3.08\,w\,h_c\,F_{pcl}\,; \qquad (25b)$$

and $H_{sk} = (A+B)\,[T_{sk}-(A\,T_a + B\,T_{dew})/(A+B)]$, (26)

where by definition

$$T_{oh} = (A\,T_a + B\,T_{dew})/(A+B)\,. \qquad (27)$$

T_{oh} may be also defined as the average of T_a and T_{dew} weighted by the transfer coefficients and wettedness concerned. These definitions of T_{oh} parallel the classic definitions for operative temperature and mean radiant temperature. The use of Eq (24) will cause a variation in T_{oh} of $\pm 2\%$.

In Fig. 5 for a sedentary subject the older ASHRAE effective temperature has been compared with humid operative temperature for three levels of clothing insulation (1.4, 1.0, and 0.6 clo). At 100% rh the reader will quickly recognize from Eq (27) that $T_a = T_{oh} = T_{eff}$. As the humidity is dropped to 35%, the best fit between the T_{eff} (old) and T_{oh} occurs for 1 clo, which clothing insulation corresponds to garments worn by Houghton and Yaglou's subjects in 1923. The greatest discrepancy for the 1 clo curve is approximately 1 C (2 F) and occurs towards the cooler temperatures. Over the range of regulation w_{rsw} = 0.2 to 1.0 the agreement between T_{oh} and T_{eff} is within 1 F. In general for 1 clo, T_{eff} tends to over-exaggerate slightly the effect of humidity in the cold and underestimate its effect in warmth.

From Fig. 5 it is possible to conclude that the older effective temperature scale of ASHRAE may have rational basis. Although it was constructed originally by empirical experimentation, it can now be derived on a physical and physiological basis. The present model makes it possible to revise the older ASHRAE T_{eff} in terms of 0.6 clo instead of the original 1 clo. The value 0.6 clo is more representative of modern everyday clothing than the heavier types used in 1923 and has been proposed by Kansas State University (KSU) as a standard for comfort analysis.

In Fig. 6 average skin temperature and wettedness predicted by our model have been plotted against humid operative temperature. Over the range of evaporative regulation (T_{oh}>75 F or 24 C) a change of humidity range from 20% to 90% causes approximately a rise of T_{sk} of 0.6 F or 0.3 C. In general the T_{sk} curves for all humidity levels parallel each other over the range of T_{oh} ranges shown. T_{sk} is thus highly correlated with T_{oh}. Since temperature sensation, which is the basis of the ASHRAE comfort scale, has been shown experimentally (Refs 8, 9, 10) to have a close correlation with skin temperature, a similar close relationship should be expected with T_{oh}. Above T_{oh} levels of 29 C or 85 F wettedness is greatly affected by the humidity level. From Eq (26) if the net heat loss from the skin surface is constant and if the mean skin temperature had remained constant, then theoretically there will be a unique one-to-

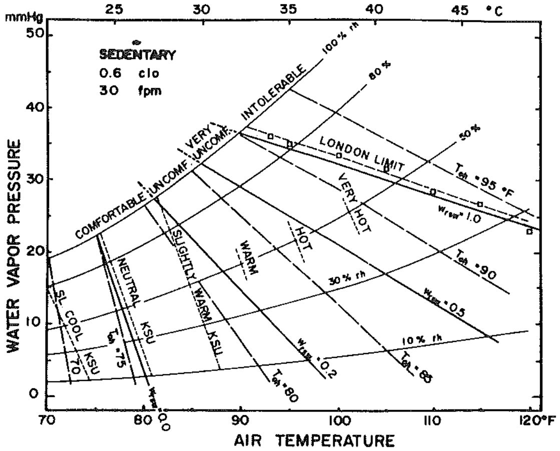

Fig. 7 Loci of constant humid operative temperature and of constant wettedness are compared with KSU measurement of temperature sensation, the Pierce Laboratory observations of warm discomfort, and the "London" limit for heat tolerance

one relation between w and T_{oh}, and the variation shown in the lower part of Fig. 6 will disappear. The important observation from this figure is that T_{oh} may be used as an index of T_{sk} within $\pm$0.5 F (0.2 C) and perhaps temperature sensation, but it is not an index of the upper limit of evaporative regulation, which is set when $w = w_{rsw} = 1$.

Comparison of Loci of Constant T_{oh} and wettedness

In Fig. 7 on a psychometric type chart with vapor pressure on the ordinate and dry bulb temperature on the abscissa lines of constant T_{oh} and constant w_{rsw} are drawn. Up to values of $w_{rsw} = 0.4$ the trends of these two types of loci are essentially parallel to each other, as may also be seen in Fig. 6. Also plotted are the latest recommended curves for "slightly cool," "comfortable" (i.e. neutral), and "slightly warm" for 1 hour exposure.[32] The T_{oh} lines may be considered somewhat similar to the old ASHRAE effective temperature scale, corrected for 0.6 clo. The KSU "comfort" line appears to fall very close to the $w_{rsw} = 0$ line or where physiological thermal neutrality occurs. Below $w_{rsw} = 0$, the remaining slope reflects the psychrometric effect of insensible evaporation from the skin and lungs. Above the $w_{rsw} = 0.5$ line the flatter slopes for the wettedness lines reflect the increasing importance of humidity.

Although a neutral temperature sensation has proved a reliable index of comfort for sedentary individuals, this same sensation may not be satisfactory to describe "comfort" during exercise or to predict "discomfort" in the zone of evaporative regulation.[10,12] In the cold temperature sensation, skin temperature, and ambient air temperature are all closely related with cold discomfort and all are associated with increased vasoconstriction before the initiation of shivering or of some type of behavioral regulation like exercising or using more clothing.

At the warm extreme the "London" limit, recommended by Ellis[2] and McArdle[33] as the upper working limit for "fit" young healthy men, has been plotted. This curve falls very near the 100% wettedness line for the new scale, although their clothing and activity levels may be different from ours. As we saw in Fig. 4 the 100% limit for an unclothed subject is very close to the upper limit for the clothed subject. Low levels of exercise will not change this limit significantly since higher metabolic levels and increased sweating rates are matched by greater values for E_{max}, as a result of the higher evaporative heat transfer coefficient due to increased air movement with exercise.

For resting subjects, when unclothed, we observed[8] that a change of 5 C (9 F) in T_a would cause approximately one category in temperature sensation vote in the cold. With exercise this was raised to 7 C (13 F). When "discomfort" is used in the cold as a category basis, approximately 10 C (18 F) would be necessary to change a vote on a discomfort scale. On a "discomfort" scale both "slightly warm" or "slightly cool" are acceptable as comfortable. The body's temperature sense is twice as sensitive in the cold to changes in skin temperature as to air temperature. Fanger[34] in an extensive study of temperature sensation, for Danish and American clothed subjects, reports an average change of 3 C (5 F) in T_a for each category vote of temperature sensation, and 5 C (9 F) for exercise. In general we can say, that, when comfort is defined as a "neutral" temperature sensation, as is the case for the majority of the ASHRAE studies to date, the resulting comfort zone is governed by the ambient and skin temperatures and less by factors caused by body temperature regulation. From Pierce data[8] in the zone of body temperature regulation the sensations of comfort and discomfort and even pleasantness and unpleasantness appear to be more associated with energy exchange and temperature regulatory processes than with temperatures of the skin or air, specially.

Construction of a new "Effective" Temperature Scale

In Fig. 8, we have traced over an ASHRAE psychrometric chart #1 scales for dry bulb and wet bulb temperatures, the mmHg at saturation, and the relative humidity curves. An extra heavy line has been drawn for the 50% rh curve. Based on data computed by the Fortran program listed in the Appendix, loci of constant wettedness caused by regulatory sweating have been drawn at 5 F (dry bulb) intervals on this heavier 50% rh curve. Where normal temperature regulation is no longer possible, these scale lines are drawn parallel to the w = 1 line toward the extreme heat and to the $w_{rsw} = 0$ line toward the cold. The w = 1 line occurs on the right at the boundary between the lightly shaded area (for uncomfortable warm) and the heavily shaded area (for intolerable). The $w_{rsw} = 0$ locus for physiological thermal neutrality passes through 77 F (25 C) on the 50% rh curve. The double shading on each side of this line represents "comfortable comfort" and closely coincides with the "neutral-comfort" recommended by the KSU group.[32] The extended lighter shading covers a broader comfort zone that includes sensations of "slightly cool" and "slightly warm." The lightly shaded area to the left of the 56 F (13 C) locus represents the beginning of an "uncomfortably cold" zone. These various loci as drawn represent the proposed new "effective temperature" scales.

In the past it has been customary to name the numerical value of an "effective temperature" scale where the loci for constant sensation or heat stress intersect the 100% rh line, where $T_a = T_{wet} = T_{dew}$. We could have done the same for the new scale. Instead we have chosen tempera-

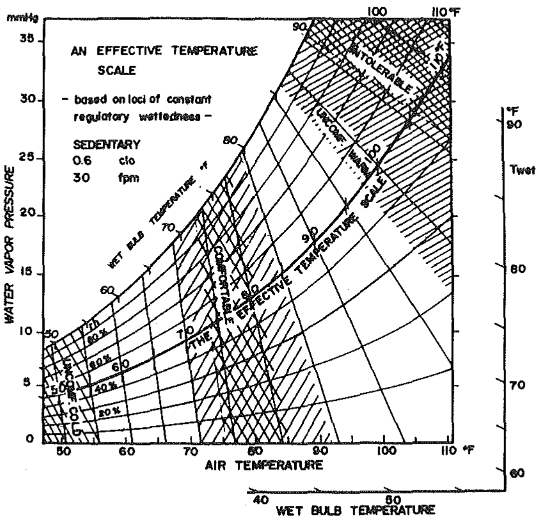

Fig. 8 A new effective temperature scale based on loci of constant wettedness caused by regulatory sweating. The lightly shaded zone on the left represents "uncomfortably cold." The lightly shaded zone on the right is "uncomfortably warm." The heavily shaded area is tolerable only for limited periods of exposure. This chart is drawn over the corresponding section of ASHRAE Psychrometric chart #1

tures on the 50% rh line for our numerical index as these values are more easily associated with environments, which we experience in our everyday living. The probable average humidity may be considered as 50%. If one had chosen the 100% rh line, the complete range of thermoregulation would cover approximately 75 F-90 F or 24 C-32 C, a numerical range currently used in the present ASHRAE effective temperature scale. On the 50% curve the same range will extend approximately 77 F-106 F or 25 C-41 C. Above and below the outer limits of regulation the change in new "effective temperature" on our new scale will follow more closely the dry bulb towards the cold and the wet bulb temperature for the extreme heat.

By using the intersection of the loci of constant skin wettedness with the dry bulb – 50% rh curve we have essentially doubled the numerical effective temperature scale over the zone of temperature regulation by sweating. However, above and below this range ($w_{rsw} = 0 - 1.0$) the new scale parallels dry bulb. In the cold the scale temperature is approximately 1 F (0.5 C) below the dry bulb. In the hot intolerable range it is consistently 16 F (9 C) above dry bulb.

Discussion

In Fig. 9 there is tabulated the general relationship between the new T_{eff} scale for sedentary clothed subjects, the thermal sensation, the physiological responses and the health factors concerned. This general chart was first presented early in 1970 to the Society by Prof. James D. Hardy, Pierce Laboratory, at the 2nd Human Factors Symposium at the ASHRAE 1970 Semiannual Meeting in San Francisco.[35] On the right side of Fig. 9 the older T_{eff} scale, corrected by T_{oh} for 0.6 clo, has been shown for comparison.

Although the present new T_{eff} does not include the effect of radiant heating, a theoretical basis has been laid to include this additional factor. Within the range of regulatory sweating and toward the cold, the Operative Temperature and the dry bulb temperature of a uniform environment are interchangeable in predicting the physiological responses and partitional calorimetry at normal humidities. There is no useable data in the literature on the combined effects of radiant heat and high humidity in the warm-uncomfortable range.

Finally, the present two-node model is not the most sophisticated available in the current literature and its usefulness is limited for exposure times shorter than an hour. However, it does include, as we know them today, all the important parameters, coefficients and controls for man and his environment necessary to predict the quasi-equilibrium status for the *whole* body and the probable values of the three principal parameters related to the judgement of comfort and thermal sensation – skin and core temperature and skin wettedness. There are many other factors involved in the judgement of comfort that have not been considered: individual skin temperatures of the hands, feet, arms, legs and trunk as well as heart rate, blood pressure, and cardiac output. These factors are important in states of severe discomfort or during heavy exercise and all must ultimately be taken into account by a more elaborate model and by more extensive experimentation, than there is available this date in the literature.

Summary

Heat balance equations for the passive state have been developed for a human subject which include the following parameters: metabolic rate, clothing insulation, dry bulb or uniform ambient temperature, humidity, and air movement. These equations are based on our latest knowledge of man's heat exchange by radiation, convection and evaporation with his environment.

A two-node model of body temperature regulation has been developed in which skin temperature and core temperature are the controllers. The threshold temperatures

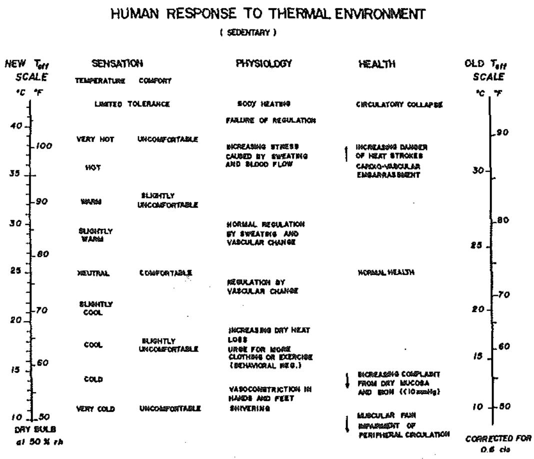

Fig. 9 An outline of response of sedentary persons to the thermal environment. (Ref Hardy, 1970)

and the control coefficients used are based on the most recent data available for *whole* man. This simple model incorporates the effector processes of vasoconstriction, vasodilation and sweat secretion.

The passive and control systems have been combined to predict the skin and core temperatures, the skin wettedness due to regulatory sweating, and the humid operative temperature for various activities and environmental stress.

Humid operative temperature (T_{oh}) is defined as the temperature of an imaginary environment to which the body will lose the same heat by radiation, convection and evaporation as in the actual environment. T_{oh}, which is derived rationally from the partitional calorimetry involved, is equal for practical purposes to the old ASHRAE effective temperature, when corrected to 0.6 clo instead of the original 1.0 clo. It is thus possible to derive the older ASHRAE T_{eff} scale rationally rather than empirically.

A new "effective temperature" scale, for a sedentary normally clothed (0.6 clo) subject, has been constructed based on loci of constant wettedness caused by regulatory sweating. The new T_{eff} scale is "named" numerically by the dry bulb temperatures at the intersection of its loci with the 50% rh curve, found on an ASHRAE psychrometric chart, rather than by the saturated temperature curve used before.

Algebraic		Unit	Fortran
S	Total body heat storage	W/sq m	STORE
S_{sk}	Heat storage of skin shell	W/sq m	HFSK
S_{cr}	Heat storage of body core	W/sq m	HFCR
M	Metabolic heat production	W/sq m	RM
E	Total evaporative heat loss	W/sq m	EV
E_{res}	Respired vapor loss	W/sq m	ERES
E_{sk}	Total skin evaporative loss	W/sq m	ESK
E_{diff}	Skin vapor loss by diffusion	W/sq m	EDIF
E_{rsw}	Skin evaporative loss by regulatory sweating	W/sq m	ERSW
E_{max}	Maximum evaporative loss from skin surface	W/sq m	EMAX
H_{sk}	Total heat loss from skin surface	W/sq m	
w	Total skin wettedness	N.D.	PWET
w_{rsw}	Wettedness due to regulatory sweat	N.D.	PRSW
w_{diff}	Skin wettedness due to diffusion	N.D.	PDIF
W	Rate of work accomplished	W/sq m	W
μ	Mechanical efficiency (W/M)	N.D.	WE
$R+C$	Total dry heat loss	W/sq m	DRY
T_a	Dry bulb or air temperature	C	TA
T_{dew}	Dew point temperature	C	TDEW
T_{wet}	Wet bulb temperature	C	TWET
ϕ_a	Relative humidity as a fraction	N.D.	RH
T_{sk}	Temperature of skin shell	C	TSK

Algebraic		Unit	Fortran
T_{cr}	Temperature of body core	C	TCR
T_{eff}	ASHRAE effective temperature	F	
P_a	Saturated vapor pressure at T_a	mmHg	PTTBL(TA)
P_{sk}	Saturated vapor pressure at T_{sk}	mmHg	PTTBL(TSK)
P_{dew}	Saturated vapor pressure at T_{dew}	mmHg	PTTBL(TDEW)
$\phi_a P_a$	Ambient vapor pressure	mmHg	PPHG
h	Combined heat transfer coefficient	W/(sq m)(C)	CTC
h_r	Linear radiation exchange coefficient	W/(sq m)(C)	CHR
h_c	Convective heat transfer coefficient	W/(sq m)(C)	CHC
I_{cl}	Insulation of clothing	clo	CLO
F_{cl}	Clothing thermal efficiency factor	N.D.	FCL
F_{pcl}	Permeation efficiency factor for clothing	N.D.	FPCL
m	Total body mass	kg	81.7
m_{sk}	Mass of skin shell	kg	3.4
m_{cr}	Mass of body core	kg	78.3
A	DuBois surface area	sq m	2.0
$\dot{V}_{bl}$	Rate of skin blood flow	1/(hr)(sq m)	SKBF
$\dot{V}_{bl\text{-}min}$	Min. skin blood flow	1/(hr)(sq m)	6.3
c_{bl}	Specific heat of blood	(W)(hr)/(kg)(C)	1.163
k_{min}	Min. skin heat conductance	W/(sq m)(C)	KMIN
c'_{sk}	Thermal capacity of skin shell	(W)(hr)/(C)	TCSK
c'_{cr}	Thermal capacity of body core	(W)(hr)/(C)	TCCR
t	Time	hr	TIME
Δt	Increment of time	hr	DTIM
$\dot{T}_{sk}$	Rate of change of T_{sk} ($\Delta T_{sk}/\Delta t$)	C/hr	
$\dot{T}_{cr}$	Rate of change of T_{cr} ($\Delta T_{cr}/\Delta t$)	C/hr	
ΔT_{sk}	Incremental change in T_{sk}	C	DTSK
ΔT_{cr}	Incremental change in T_{cr}	C	DTCR
Σ_{sk}	Skin signal	C	SKSIG
	When (+) warm signal		WARMS
	When (-) cold signal		COLDS
Σ_{cr}	Core signal	C	CRSIG
	When (+) warm signal		WARMC
	When (-) cold signal		COLDC
$\Delta T_B/\Delta t$	Change in mean body temperature (rate)	C/hr	STORC
$\dot{m}_{rsw}$	Rate of sweat secretion	g/(hr)(sq m)	REGSW

USEFUL CONVERSION FACTORS

W/sq m	to	Btu/(hr)(sq ft)	multiply by 0.317
W/(sq m)(C)	to	Btu/(hr)(sq ft)(F)	multiply by 0.176
W (hr)	to	Btu	multiply by 3.413
W (hr/g)	to	Btu/lb	multiply by 1548
W (hr)/(kg)(C)	to B	Btu/(lb)(F)	multiply by 0.860

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APPENDIX

AN ANNOTATED FORTRAN PROGRAM FOR A CORE-SHELL MODEL OF HUMAN TEMPERATURE REGULATION

```
C         THE ENVIRONMENTAL FACTORS AND THE TYPE OF ACTIVITY
C      ARE DEFINED IN AN INITIAL 'READ' STATEMENT BY
C              RM,WE,CTC,CLO,TA,RH
C      A 'DO' STATEMENT MAY BE USED FOR TA OR RH OR BOTH

C STANDARD MAN IS 81.7KG 1.77M HT AND 2.0 SQ.M DUBOIS AREA
C IN PROGRAM 1.163=CONV. FACTOR KCAL/HR TO WATTS
C             1.163=SPECIFIC HEAT OF BLOOD IN W*HR/(L*C)
C             0.7=LATENT HEAT IN WATT*HR/G
C             0.97=SPECIFIC HEAT OF BODY IN W*HR/(KG*C)
C             2.2=LEWIS RELATION

C INITIAL CONDITIONS - BODY IN PHYSIOL. THERMAL EQUILIBRIUM
      REAL KMIN
      TSK=34.1
      TCR=36.6
      ERES=0.0023*RM*(44.-RH*PTTBL(TA))
C  PTTBL(TA) IS FUNCTION FOR VAPOR PRESSURE(MMHG) AT TEMP. TA DEG. C
      EDIF=5.0
      EV=ERES+EDIF
      ERSW=0.0
      EDRIP=0.
C.  EDRIP IS UNEVAPORATED SWEAT FROM SKIN SURFACE
      WRSW=0.0
      CHR=5.23
      CHC=CTC-CHR
      WK=WE*RM
C   FOR NEXT TWO CARDS SEE REF.21
      FCL=1./(1.+0.155*CTC*CLO)
      FPCL=1./(1.+0.143*(CTC-CHR)*CLO)
C KMIN = MIN. CONDUCTANCE IN W/(SQ.M*C)
      KMIN=5.28
C SKBFN = NORMAL SKIN BLOOD FLOW L/(SQ.M*HR)
      SKBFN=6.3
      SKBF=SKBFN
      TIME=0.0

  600 CONTINUE

C HEAT BALANCE EQUATIONS  FOR PASSIVE SYSTEM

C HEAT FLOW FROM CORE TO SKIN TO AIR IN W/SQ.M
      HFCR=RM-(TCR-TSK)*(KMIN+1.163*SKBF)-ERES-WK
      HFSK=(TCR-TSK)*(KMIN+1.163*SKBF)-CTC*(TSK-TA)*FCL-(EV-ERES)

C THERMAL CAPACITY OF SKIN SHELL FOR AV. MAN IN W.HR/C
      TCSK=0.97*3.4
C THERMAL CAPACITY OF CORE FOR AV. MAN IN W.HR/C
      TCCR=0.97*78.3
C CHANGE IN SKIN SHELL AND CORE IN DEG. C PER HOUR
      DTSK=(HFSK*2.0)/TCSK
      DTCR=(HFCR*2.0)/TCCR
C NOTE UNIT OF TIME IS ONE HOUR
      DTIM= 1./60.
```

```
C TO ADJUST INTEGRATION OVER SMALL STEPS IN DTSK AND DTCR
      U=ABS(DTSK)
      IF(U*DTIM-0.1) 873,873,874
  874 DTIM=0.1/U
  873 CONTINUE
      U=ABS(DTCR)
      IF(U*DTIM-0.1) 973,973,974
  974 DTIM=0.1/U
  973 CONTINUE
      TIME=TIME+DTIM
      TSK=TSK+DTSK*DTIM
      TCR=TCR+DTCR*DTIM

C CONTROL SYSTEM
C DEFINING SIG. FOR CONTROLS FOR VASO-CONSTRICT.-DILATION
C FROM SKIN
      SKSIG=(TSK-34.1)
      IF(SKSIG)900,900,901
  900 COLDS=-SKSIG
      WARMS=0.0
      GO TO 902
  901 COLDS=0.0
      WARMS=SKSIG
C FROM CORE
   902 CRSIG=(TCR-36.6)
      IF(CRSIG)800,800,801
  800 COLDC=-CRSIG
      WARMC=0.0
      GO TO 802
  801 WARMC=CRSIG
      COLDC=0.0
C FACTORS 0.5(COLD) AND 75.(WARM) GOVERN STRIC AND DILAT SEE NEXT 2 CARDS
  802 STRIC=0.5*COLDS
      DILAT= 75.*WARMC
C  CONTROL OF SKIN BLOOD FLOW
      SKBF=(SKBFN+DILAT)/(1.+STRIC)
C CONTROL OF REG. SWEATING
C REGSW IN G/(SQ.M*HR)
C DURING REST
      IF(RM-60.)401,401,402
  401 REGSW=100.*WARMC*WARMS
      GO TO 403
C DURING EXERCISE
  402 REGSW=250.*WARMC+100.*WARMC*WARMS
C BULLARD VAN BEAUMONT EFFECT, MODIFIED BY STOLWIJK
  403 ERSW=0.7*REGSW*2.**((TSK-34.1)/3.)
C TO AVOID IMPOSSIBLE SOLUTIONS MAX. REGSW IS 16 G/MIN
      IF(ERSW -500.)404,404,100

C  WRSW IS REG. SWEAT IN 100CC UNITS PER MAN FOR TIME EXP.
  404 WRSW= WRSW+ (ERSW*2.0/(0.7* 100.))*DTIM
      EMAX=2.2*CHC*(PTTBL(TSK)-RH*PTTBL(TA))*FPCL
      PRSW=ERSW/EMAX
      PWET=(0.06+0.94*PRSW)
```

```
C NOTE TOTAL EVAPORATIVE LOSS FROM SKIN IS PWET*EMAX
      EDIF=PWET*EMAX-ERSW
      EV=ERES+ERSW+EDIF
      IF(ERSW-EMAX)220,220,201
  201 EDRIP=ERSW-EMAX
      EV=ERES+EMAX
      ERSW=EMAX
      EDIF=0.0
      PRSW=1.0
      PWET=1.0
  220 CONTINUE

C TO CALCULATE QUASI-EQUILIBRIUM AFTER ONE HOUR EXPOSURE
      IF(TIME-1.00) 600,601,601
C THE EXPOSURE TIME (1.00) CAN BE CHANGED UP OR DOWN TO 0.25
  601 CONTINUE
      DRY=CTC*(TSK-TA)*FCL
C STORE IN WATT PER SQ.METER   STORC IN DEG.C PER HOUR
C STORE IS ALSO EQUAL TO HFSK PLUS HFCR
      STORE=RM-EV-DRY-WK
      STORC=STORE*2.0/(81.7*0.97)

C CALCULATION TWET FROM TA AND RH
      TWET=TA
 1204 E=RH-(PTTBL(TWET)-0.00066*760.*(TA-TWET)*
     X  (1.0+0.00115*TWET))/PTTBL(TA)
      IF(E)1203,1202,1202
 1203 TWET=TWET-0.10
      GO TO 1204
 1202 CONTINUE

C CALCULATE TDEW
      TDEW=-10.
 1702 X= PTTBL(TWET)-(TA-TWET)/2.
      DDEW=(PTTBL(TDEW)-X)
      IF(DDEW)1700,1701,1701
 1700 TDEW=TDEW+0.10
      GO TO 1702
 1701 CONTINUE

C   THE NISHI ENVIRONMENTAL EQUATIONS
      XA=FCL*CTC
      XB=2.2*1.4*CHC*FPCL
      TOH=(XA*TA+PWET*XB*TDEW)/(XA+PWET*XB)

C ADD CARDS FOR PRINTOUT OF HEAT EXCHANGE DATA
C ADD CARDS FOR PRINTOUT OF PHYSIOLOGICAL DATA

  100 CONTINUE
      END
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DISCUSSION

P.E. McNALL, JR., (Kansas State University, Manhattan, Kan.): I think this is a very good piece of work, Dr. Gagge, and I wonder now whether this scale shouldn't have a name. In other words, call it something different from "effective temperature" since this does have a meaning to many of us in the Society and if we could think up a good new term for it, it might increase its use and solve the problem of confusion in the future.

I would suggest that if we have to borrow a term, that we borrow one from some other area that is not well known to ASHRAE. Perhaps the physiological literature has terms which we could use.

Also, as many of you know, we are rewriting the chapter on comfort in ASHRAE HANDBOOK OF FUNDAMENTALS. This new scale certainly should be covered there. Let's see if we can't do something with that terminology so that we don't add to the confusion in the future.

J.D. HARDY, (John B. Pierce Foundation, New Haven, Conn.): Dr. McNall has raised the important point of what to call Dr. Gagge's proposed "new effective temperature scale." At the 1970 Semiannual Meeting, using many of the considerations presented in Dr. Gagge's paper, I suggested the term "Comfort-Health-Index" or "CHI" to replace the usual THI or "Temperature-Humidity-Index." Since the proposed scale is not truly a temperature scale perhaps the term index might be more appropriate.

DR. GAGGE: We can answer rather simply both Dr. McNall's and Dr. Hardy's question, whether or not to call our proposed scale a "temperature" or an "index." "Temperature" should refer to a rationally derived or measurable quantity, and one with a defined physical meaning. "Operative" temperature, as described by us in the past had such a meaning, can be used in a heat balance equation describing man's heat exchange with his environment. "Effective Temperature," as used by ASHRAE, should have been calssified as an "Index" but not as a "Temperature," since it never has had any meaning in a heat balance equation. Our present proposal, illustrated in Fig. 8, must be classified as an "index" as the indicated temperature has no meaning in a heat balance equation.

The use of the words "Comfort-Health," as descriptive names for an index, has its virtues. The proposed new effective temperature scale has a psychological, physiological and health basis as seen in Fig. 9 and, by using an equivalent 50% RH value for all scale values, the index will coincide more with man's human every day experience. We accept Dr. Hardy's suggestion that an appropriate name for the scale illustrated in Fig. 8 is a "Comfort-Health-Index" (CHI).

The concept of "Humid Operative Temperature" (T_{oh}), as an imaginary temperature at saturation, is a rationally derived temperature and does have a meaning in the heat balance equation. This temperature has biometeorological significance and by definition relates the exchange of heat from average skin temperature $\overline{T}_{sk}$ to the environment by radiation, convection and evaporation.

F.H. FULLER (E.I. duPont de Nemours, Wilmington, Del.): I would agree that you should change the name of effective temperature to something else, except that it has taken 15 to 20 years to get my management to think in terms of effective temperature. Effective temperature is an accepted term that would be hard to change.

Some years ago, Mosher of Kodak put together a chart based on some old work of ASHRAE. He plotted maximum effective temperature versus metabolic rate. This chart has been quite useful to the ventilation and air-conditioning engineers. Do you intend to develop such a plot or to extend your research so that you can develop such a plot?

DR. GAGGE: I am unfamiliar with Dr. Mosher's work at Kodak and evidently he did not publish his ideas in our TRANSACTIONS. In general the present proposed Effective Temperature Index (ETI) and as illustrated in our Fig. 8 has significance only for sedentary subjects. Its relationship to the corresponding psychological, physiological and health factors is shown in Fig. 9. As was the case for the old ET, it is possible to average rationally the combined thermal effects caused by various combinations of clothing, air movement and radiant heating and to express as a single temperature on the abscissa of Fig. 8, by using a concept we suggested several years ago "Standard Operative Temperature" (see Am. J. Physiol. 131, 93-103, 1940 and J. Appl. Physiol. 23, 248-258, 1967).

For each new level of activity (increasing metabolic rate) there will be both a new and lower ambient temperature for comfort as well as a lower skin temperature for a "neutral" Temperature Sensation, as was shown by Fanger (1967) and McNall et al. (1967). In an earlier paper (see Ref 12) we suggested a skin wettedness of 20% could serve as a common index for an upper limit for comfort over quite a range of exercise activities.

The use of a physiological basis for an "Effective Temperature" scale is not new. Yaglou, in paper #1319 ASH&VE TRANSACTIONS 1947, proposed lines of constant skin temperature be used as an index. The difficulty of using skin temperature as a basis of thermal comfort has been shown by Chatonet and Cabanac (Ref 6) who demonstrated that temperature and comfort sensation are affected also by changing internal body temperature with activity.

Our recommendation for a proposed CHI is limited in the present paper to sedentary conditions for which there is a sound and extensive experimental basis thanks to the efforts of the KSU-ASHRAE studies under the direction of Dr. Ralph Nevins and Dr. Preston McNall. Analytically, we are also proposing a method, that is rational physically, to extend our predictions to other activity levels for which there is still a need for a great deal more experimental data.

P.O. FANGER, (Technical University of Denmark, Copenhagen, Denmark): The authors should be complimented on their important and most interesting research work.

Their two-node model is derived in an elegant way by combining equations describing in detail the passive and the controlling system of man's thermo-regulation. This model, including the corresponding computer program, has here been used to develop a new effective temperature scale which will undoubtedly be a most useful tool in the future, also for other applications.

In my opinion, the authors present a solid foundation for the new effective temperature diagram, applicable to sedentary subjects at low velocity, clothed in 0.6 clo, and mean radiant temperature equal to air temperature. On the basis of the same model, analogous diagrams can be drawn up showing the significance of humidity at other combinations of the parameters.

I am not, however, in agreement with the authors' comparison with the old ASHRAE effective temperature scale, which in my opinion accords far too great an influence to humidity in the comfort zone.

The authors conclude tha the old ASHRAE effective temperature scale may have a rational basis. Admittedly, the old scale gives a significantly greater humidity dependence than the present study, but according to the authors, this is due to the clothing at the time being 1 clo, and it is maintained that the difference is slight when converted to 0.6 clo.

It should be remembered, however, that Yaglou et al. drew up not only a "normal" effective temperature scale (Ref a, 1925) for subjects wearing customary indoor clothing (~ 1 clo), but also a "basic" effective temperature scale (Ref 1), which was drawn up already in 1923 for semi-nude subjects. The two scales show a moderate difference, but contrary to the clothing correction in the present paper, Yaglou found greater humidity dependence for the semi-nude persons than for the clothed.

From the curves of the new effective temperature lines in the comfort zone (and colder) it will be found that a change from RH=0% to RH=100% corresponds to a temperature change of ~ 5F (Fig. 8) compared with 12-16 F from Yaglou's diagrams.

I therefore take the results of the present excellent investigation as a new confirmation of the far too great humidity dependence in the old effective temperature scale at low and moderate temperatures. The old scale has for many years been the cause of numerous misunderstandings among engineers. It should be replaced as soon as possible by a scale such as the present one which shows the humidity influence on a rational basis.

One final question: In the paper the authors derive expressions both for wettedness and for humid operative temperature. I should like to know why the authors finally chose to base the new scale on loci of constant wettedness and not on loci of constant operative temperature.

REFERENCES

a. C.P. Yaglou and W. Edw. Miller, Effective Temperature with Clothing. ASH&VE Vol 31, pp 89-99, 1925.

DR. GAGGE: We agree with everything you say about the older ET scale. A careful comparison of our humid operative temperature scale (T_{oh}) for 1 clo with the old ET value does correct the older scale in the directions you indicate are so necessary. A more exact equation (see Eq 27) relating the vapor pressure gradient to the difference between T_{sk} and T_{dew} perhaps would improve the accuracy of this correction.

We pointed out in our text that, if skin temperature had remained constant over the whole range of skin wettedness from 0 to 100%, then lines of constant wettedness would have coincided with lines of constant humid operative temperature (T_{oh}). However, such a model ($\overline{T}_{sk} \sim$ const) would require an infinitely thin skin shell and a uniformly heated core. This does not exist in nature. Since skin blood flow is so essential for body temperature regulation, and since the skin shell has a finite mass, $\overline{T}_{sk}$ must vary with the environmental temperature and thus in a "living" model lines of constant wettedness never coincide with lines of constant T_{oh} except when there is no skin sweating. As said in text, loci of constant wettedness are associated more closely with "Discomfort." Loci of constant skin temperature follow loci of constant T_{oh}, and hence with temperature sensation, which is the classical ASHRAE definition of comfort. Since health and heat tolerance considerations are governed by skin wettedness and since in the comfort zone, while sedentary, there is little significant difference between the two concepts, we chose loci of constant wettedness as the physiological basis for the new CHI.