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A STANDARD PREDICTIVE INDEX OF HUMAN RESPONSE TO THE THERMAL ENVIRONMENT

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ABSTRACT

Temperature and sensory indices of human response to the thermal environment are often expressed in terms of the known response in a controlled laboratory environment, as a standard. The three rational indices of this type to be considered are (1) ASHRAE's Standard Effective Temperature (SET*) Index, defined as the equivalent dry bulb temperature of an isothermal environment at 50% RH in which a subject, while wearing clothing standardized for activity concerned, would have the same heat stress (skin temperature T_{sk}) and thermoregulatory strain (skin wettedness, w) as in the actual test environment; (2) Fanger's Predicted Mean Vote (PMV) Index, defined in terms of the heat load that would be required to restore a state of "Comfort" and evaluated by his Comfort Equation; and (3) Winslow's Skin Wettedness Index of "Thermal Discomfort" (DISC) defined in terms of the fraction of the body surface, wet with perspiration, required to regulate body temperature by evaporative cooling. The classic difference between PMV and DISC as predictors of warm discomfort occurs at very high and very low humidity but both lead to essentially the same judgment at average humidities (40-60% RH or 1-2 kPa). A new index PMV* is proposed for any dry or humid environment by simply replacing operative temperature T_o in Fanger's Comfort Equation with SET*. The use of PMV* as a sensor of heat stress and strain, is illustrated for typical HVAC situations and with a new Comfort-Humidity psychometric chart for indoor environments.

INTRODUCTION

Successful indices of human response to the thermal environment are based on (a) a rational model of energy exchange between the skin surface and the ambient environment, as described by operative temperature (T_o) and dew point temperature (T_{dp}), and their associated heat and mass transfer coefficients; (b) how the human regulates its internal temperature at a relatively constant level by sweating, vascular changes and shivering; and (c) how the two dependent physical properties of the body's skin surface, namely mean skin temperature (T_{sk}) and skin wettedness (w) caused by perspiration, affect sensations of "warmth and cold" and of "comfort and discomfort".

All rational sensory and thermal indices, such as Fanger's comfort equation [1], Winslow's pleasantness-skin wettedness relation [2] and Belding's Heat Stress Index [3] are based on some component of the body heat balance equation (1st Law), which describes quantitatively the entire energy exchange at the skin surface. The state of our knowledge of human response to the thermal environment is well summarized in the ASHRAE Fundamentals [4] and the American Physiological Society's Handbooks [5] and other comprehensive and pertinent review articles [6], [7] and [8].

The present paper outlines briefly present concepts of Temperature and Sensory Indices, as developed over the past 60 years and shows how they may be combined as a single standard index of Comfort, Health and Performance during rest and exercise.

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THE HUMAN HEAT BALANCE EQUATION AND ITS SIGNIFICANCE

The simplest model of human temperature regulation and heat exchange in various environments considers the body's skin surface as the boundary between man and his thermal environment. Metabolic heat is transported by conduction and skin blood flow from the body's interior core at uniform temperature (T_c) to the skin surface at temperature (T_{sk}). The net heat flow to the skin surface (H_{sk}) is measurable as metabolic heat (M) less work accomplished (W) less respired heat by both evaporation (E_{res}) and convection (C_{res}). The heat loss from the skin surface (also H_{sk}) to environment is divided into two parts: 1) the <u>sensible</u> (DRY) by conduction through clothing and by radiation and convection from the body surface; and 2) the <u>insensible</u> (E_{sk}), by evaporation of perspiration on the skin surface. Sensible heat exchange is governed by a combined heat transfer coefficient (h') over the gradient ($T_{sk} - T_o$), where T_o is the operative temperature of the environment, defined as the average of ambient air temperature (T_a) and the mean radiant temperature (MRT), weighted by their respective linear heat transfer coefficients h_c and h_r. Insensible heat is controlled by a combined evaporative heat transfer coefficient (wh'_e) over the gradient ($P_{ssk} - P_{sdp}$), where P_{ssk} and P_{sdp} are saturation vapor pressures at skin and ambient dew point temperatures. Skin wettedness (w) is the second physical property of the skin surface and is defined as the fraction of its total surface wet with perspiration. All evaporative heat loss is assumed to occur on the skin surface itself, and the laws of mass transfer govern the flow of water vapor from skin surface through clothing to the environment. P_{sdp} is the ambient vapor pressure (P_a) and equals the product (rh).P_{sa}, where rh is relative humidity as a fraction and P_{sa} the saturated vapor pressure at the ambient temperature T_a. The combined coefficients h' and h'_e in eq. (1) are both functions of the ambient air movement (V), of the intrinsic insulation (I_{cl}) of clothing worn and of the vapor resistance of clothing (I_{cl}/i_{cl})/L_a, where i_{cl} is a measure (N.D.) of vapor permeability efficiency of the clothing layer itself (9), and L_a is the Lewis Relation for air in K/kPa units. h' and h'_e are customarily defined in watts per square metre of skin surface (as evaluated by the classic DuBois Height-Weight-Area relationship) over the temperature (K) and vapor pressure (kPa) gradients respectively. All the above statements are reflected in the following generalized Body Heat Balance Equations, which describe the heat exchange H_{sk} at the skin surface with environment as

$$H_{sk} = h'(T_{sk} - T_o) + wh'_e(P_{ssk} - P_{sdp}), \qquad Wm^{-2} \qquad (1)$$

and heat flow to the skin surface from the body core as

$$H_{sk} = M - W - (E_{res} + C_{res}) - (\pm S) \quad . \qquad (2)$$

The term (± S) for heat storage (+ for body heating, - for body cooling) occurs when there is no thermal equilibrium. When the body succeeds in regulating its mean temperature (T_b) at a relatively constant level, S is zero. The primary heat source in H_{sk} is metabolic.

The insensible term [wh'_e ($P_{ssk} - P_{sdp}$)], in equation 1 describes the total skin evaporation E_{sk} at the skin surface. E_{sk} in turn consists of E_{diff}, the evaporative heat of moisture diffusing through the skin surface, and E_{sw}, the evaporative heat caused by regulatory sweating. Theoretically, the maximum evaporative cooling possible from the skin surface (E_{max}) occurs when w = 1. Skin wettedness may be re-defined from equation (1) and (2) as the ratio

$$w = E_{sk}/E_{max} \qquad (3),$$

or

$$= [H_{sk} - h'(T_{sk} - T_o)]/[h'_e(P_{ssk} - P_{sdp})] \ , \qquad kP_a/K \qquad (3)$$

Wettedness (w) ranges from a value of about 0.06 caused by E_{diff} alone, to 1.0, when the skin surface is theoretically totally wet with perspiration, a condition that occurs rarely in practice. A critical wettedness (w_{crit}) between 0.7 and 1.0 likely exists, when efficiency of evaporative regulation begins to fail [10,11].

Appendix (A) defines all the parameters and physical factors involved in the combined heat (h') and mass (h'_e) transfer coefficients in equation (1)-(3).

THE EFFECTIVE TEMPERATURE CONCEPT

The rational Effective Temperature (ET*) as ASHRAE uses it today, is defined as the hypothetical dry bulb temperature of an isothermal environment at 50% RH in which a human subject would have the same skin wettedness (w) and heat exchange (H_{sk}) at the skin surface as in the actual test environment, described by temperature T_o and ambient vapor pressure P_a. By this definition, Eq. 1 becomes

$$H_{sk} = h'(T_{sk} - ET^*) + wh'_e(P_{ssk} - 0.5\ P_{sET^*}) \qquad W/m^2 \qquad (4)$$

From Eq. 1 and 4, ET* is the solution of

$$(T_o - ET^*) + (wh'_e/h')(P_a - 0.5\ P_{sET^*}) = 0 \qquad °C \qquad (5)$$

Where w is evaluated for T_o and P_a by Eq. 3' above

Thus, ET* is a function of the physical factors describing the test environment, namely T_o, P_a, the transfer coefficients h' and h'_e and the resulting skin wettedness (w). The term (wh'_e/h') is the effective psychrometric ratio for energy exchanged by insensible and sensible heat at the skin surface of a clothed subject while regulating his body temperature in warm environments by perspiration.

A Mollier type psychrometric chart (Fig. 1) with temperature (T_a or T_o) on the ordinate and ambient vapor pressure (P_a) on the abscissa illustrates the relationship between w, ET* and the environmental variables at 10, 20, 50, 80 and 100% RH. A dynamic model of "human temperature regulation", based on accepted physiological principles and described in Appendix B, has been used to develop values for T_{sk} and skin wettedness w over the temperature (10° - 50° C) and humidity (1 - 5 kPa) ranges at fixed levels of activity and clothing worn. The applicable heat transfer factors are indicated in upper left corner. Each ET* locus is identified by the temperature on the ordinate at its intersection with the 50% RH curve and describes the T_o and P_a values, which ultimately result in a constant skin wettedness. As wettedness due to regulatory sweating increases towards warmer temperatures, the negative slope (wh'_e/h') for each ET* locus also increases. Toward the cold ET* loci become essentially horizontal and are unaffected by humidity.

The maximum negative slope for ET* loci occurs theoretically when $w = w_{crit}$, as mentioned above. The ET* locus corresponding to w_{crit} serves as the upper limit in Fig. 1 for the effective E_{max}. All ET* loci at and above $w = w_{crit}$ become parallel with constant negative slopes. For the present paper $w_{crit} = 0.85$ is chosen as a practical value to illustrate our present objectives.

ET* loci in Fig. 1 have a meteorological significance as lines of constant enthalpy of a humid environment for a "clothed human subject with skin wettedness w". The negative slope of the ET* locus describes the effective psychrometric ratio for energy exchange at the skin surface with wettedness w. The locus, drawn in Fig. 1 for w = 0.85 at 40°C ET*, has a negative slope of about 6.6 K/kPa (see Table 1). For comparison, the negative slope of a wet bulb locus if drawn through 40° and 50% RH would be about 17 K/kPa, a value which approximates in magnitude the value of the Lewis Relation (L_a) for air layer over fully wet skin at 37.5°C.

TEMPERATURE SENSATIONS, AS PREDICTED BY FANGER'S COMFORT EQUATION

The most widely accepted index of thermal sensation today is Fanger's "Predicted Mean Vote" (PMV) [1]. He defines PMV in terms of thermal load (L), measured as the net metabolic heat produced at the skin surface less the total sensible heat loss when a human is exposed to the environment. In the heat (+ L) is the rate of evaporative cooling required to maintain comfort and thermal equilibrium. In the cold (- L) is the rate of body heating required to maintain Comfort and thermal equilibrium. A state of Comfort with neutral thermal sensation exists when L = 0.

In the Comfort Equation for positive loads (+ L), Fanger considers the total skin evaporation as three components: namely

$$E_{sk} = E_{diff} + E_{comf} + E_{rsw}, \qquad Wm^{-2} \qquad (6)$$

where E_{diff} is the evaporative heat loss caused by diffusion of moisture through the skin and is approximately 6% of E_{max} when no sweating is present E_{comf} is the evaporative loss by sweating that occurs during a state of "Comfort" and is evaluated by Fanger as 0.42 (M - W - 58.2). During rest (M = 58.2), E_{comf} is zero and increases with activity when M is greater than 58.2. Recent studies [13] suggest that E_{comf} may be a consequence of the reflex sweating and vasodilation associated primarily with the rising body temperature due to exercise itself and is not necessarily a thermoregulatory compensation due to heat stress from the environment. E_{rsw} is by difference the evaporative heat loss by the sweating required for regulation of body temperature as the environment becomes warmer. The total evaporative loss by sweating E_{sw} is either $(E_{rsw} + E_{comf})$ or $(E_{sk} - E_{diff})$.

Fanger's original Comfort Equation for PMV in terms of heat load (+ L) may now be rewritten by eq. (1) and (6) as:

$$PMV = \alpha[H_{sk} - h'(T_{sk} - T_o) - E_{diff} - E_{comf}] \quad N.D. \quad (7)$$

or $$= \alpha[E_{sk} - (E_{comf} + E_{diff})] \quad (8)$$

or $$= \alpha[E_{sw} - E_{comf}] \text{ or } \alpha[E_{rsw}] \quad . \quad (8)'$$

where $$\alpha = 0.303^* \exp(-0.036M) + 0.028 \quad (8)''$$

In Eq. (7), α is a sensitivity factor, which Fanger observed to decrease rapidly from 0.06 during rest to a relatively constant level of 0.03 after resting metabolism (M) doubles. The energy equivalent of E_{diff} is about 5% of M.

In the cold (- L), where $E_{rsw} = 0$ and E_{comf} diminishes rapidly as vasoconstriction begins, Fanger's Comfort equation reduces to:

$$\text{neg. } PMV = \alpha[(h'(T_{sk} - T_o) + (E_{diff} + E_{comf}) - H_{sk}] \quad N.D. \quad (9)$$

or

$$= \alpha[- S], \text{ which varies as the rate of fall of mean body temperature } (-T_b).$$

Natural protection from cold is first accomplished by vasoconstriction of blood flow to the skin surface and secondarily by shivering. Use of insulative clothing is man's behavioral method for protection against cold. Voluntarily increasing activity is a fourth method for preventing cold. When all else fails, he turns on the heat or runs for cover.

Currently ASHRAE uses Fanger's nine point psychophysical scale for PMV: very cold (- 4), cold (- 3), cool (- 2), slightly cool (- 1), neutral and comfortable (0), slightly warm (+ 1), warm (+ 2), hot (+ 3), very hot (+ 4). To this scale may be added a fifth pair (±5) "intolerable". Fanger validated his PMV over the range ± 3 at normal ambient vapor pressures 1-2 kPa (10-20 mB) or 40-60% RH with over 1500 subjects.

COMFORT - AS A SENSE OF PLEASANTNESS AND OF MINIMAL THERMOREGULATORY STRAIN

In 1939 Winslow et al. (2) at the Pierce Laboratory, observed that in warm climates a sense of "pleasantness" and "comfort" was associated with low values of skin wettedness, which can be measured quantitatively as the ratio E_{sk}/E_{max} used in Eq. (3) above. In other words, warm discomfort (DISC) is linearly proportional to skin wettedness w or the fraction of the body surface wet with perspiration. In 1969, stimulated by Fanger's novel PMV Concepts and the increasing interest in Comfort during exercise, we observed (14) that for subjects exercising on a bicycle ergometer there was a threshold wettedness, w_o or E_o/E_{max}, associated with Comfort (or zero DISC), and that wo increased with activity in almost the same proportion as Fanger's threshold factor $(E_{comf} + E_{diff})$.

We now redefine thermal discomfort (DISC) as the relative thermoregulatory strain necessary to restore a state of comfort and thermal equilibrium by sweating and we use wo as the threshold wettedness for comfort.

Thus $$DISC = \beta[(w - w_o)/(w_{crit} - w_o)], \quad N.D. \quad (10)$$

where $$w = E_{sk}/E_{max} \text{ or } (E_{sw} + E_{diff})/E_{max}, \quad (11)$$

and $$w_o = (E_{comf} + E_{diff})/E_{max} \quad . \quad (12)$$

Comparing Eq. (8) and (10), both DISC and PMV are zero when "comfortable" and "neutral". DISC and PMV would also be numerically equal when w equals w_{crit}, where the sensitivity coefficient β equals numerically the product of α and $(w_{crit}.E_{max})$. When Eq. 10 is used to estimate DISC in examples to follow, β has been logically set at five.

The term "strain" is used above in a physiological sense as the regulatory effort, caused by both activating the number of sweat glands and increasing their flow to the skin surface to form the area of wetted skin surface needed for the evaporative cooling E_{sw} (or $E_{rsw} + E_{comf}$) to regulate body temperature. When the required E_{sw} exceeds E_{max} at w_{crit}, unevaporated sweat may wick into the clothing layers or drip from the skin surface. Then, the cooling efficiency of regulatory sweating drops rapidly.

The phrase "Discomfort" as used above applies primarily to warm environments, in which regulation of body temperature is accomplished by the evaporation of regulatory sweat on skin surface. The counterpart of "Discomfort" in the cold would be the "strain" necessary to vasoconstrict and shiver. Shivering can raise metabolic heat production as high as three times resting rate. Complete vasoconstriction of normal blood flow to skin surface would be like putting on a light sweater (∿ 0.5 Clo). Both processes would produce an apparent "warmth" sensation.

DISC is described numerically as: comfortable and pleasant (0), slightly uncomfortable but acceptable (1), uncomfortable and unpleasant (2), very uncomfortable (3), limited tolerance (4), and intolerable (5). The range of each category is ± 0.5 numerically. In the cold, the classical negative category descriptions used for Fanger's PMV apply.

RELATIONSHIP BETWEEN ± PMV, DISC AND ET* AND THE NEW PMV*

Isotherms for PMV and DISC, as defined by Eq. (9) and (10), are plotted in Fig. 2 on the same type of psychrometric chart used in Fig. 1. PMV isotherms, as defined by Fanger, are almost horizontal and parallel; which would indicate humidity itself has little effect on thermal sensation. DISC-isotherms in contrast do vary with humidity and have changing negative slopes very similar to those for ET* in Fig. 1.

Figure 3 indicates how DISC varies with T_a at 20, 50 and 80% RH. The variation of PMV with T_a at 50% is drawn as a solid line. The PMV loci for 20% and 80% RH are dashed lines paralleling the one for 50% and are displaced approximately ± 1° (on abscissa).

The inset in Fig. 3 shows that there is little difference between the meaning or intent of PMV and DISC category judgments for T_a at 50% RH or ET*. As temperatures rise above the comfort point at 24°C, PMV increases at a slightly greater rate than DISC. Near the critical point (w = 0.85), the opposite is true. The two sensations in terms of ET* differ by less than a half category at 32-33°. Where RH > 50%, ET* is greater than the ambient T_a. The opposite is true when RH < 50%. Since PMV values are based primarily on T_a or T_o, they tend to exaggerate temperature sensation, discomfort and unacceptability at low humidities, such as in desert climates (where P_a is less than 0.05 kPa). In wet tropical climates, where P_a is greater than 3 kPa, PMV underestimates the apparent temperature sensation, warm discomfort and unacceptability.

Since <u>any</u> environment can be described in terms of ET* by Eq. 4 or 5 above, we propose that significant differences in meaning or intent between +DISC and +PMV at high and low humidities may be eliminated by using ET* in the place of T_o in Fanger's Comfort Equation (7) above. ET* is a better temperature measure than To of the enthalpy of the total humid-clothing environment, surrounding the wet skin surface. Such an index, named here PMV*, is the counterpart to ET* and serves as a combined biophysical, physiological and sensory index of human response to the humid environment. In Fig. 1, the coordinates of each point on an ET* loci describe P_a, T_o values that would result in the same total energy exchange at the skin surface, i.e. H_{sk} in eq. (1). Fig. 4 demonstrates how both PMV* and DISC are equally sensitive to low and high humidity over the ambient temperature range 20-40° C. The ordinate scale indicates five category descriptions proposed for PMV* in warm climates. Toward the cold, category descriptions for - PMV* and - PMV remain unchanged.

THE STANDARD TEMPERATURE INDICES

In a previous section, we demonstrated how ET* and the slope of its loci on a psychrometric chart are basic biophysical descriptions of human heat exchange in the living environment. The example, shown in Fig. 1, describes the heat exchange of a sedentary subject, normally clothed, for typical indoor environments. Figures 2, 3 and 4 demonstrate how the two classic indices of temperature sensation (PMV) and warm discomfort (DISC) may be combined as generalized index PMV*, which is directly related to ET* and is responsive to humidity changes in the actual environment. The present section will carry the concept of equivalent environments through another stage; whereby <u>Standard Effective Temepratur</u>e (SET*) is defined as the dry bulb temperature of a hypothetical isothermal environment at 50% RH in which a human subject, while wearing clothing, standardized for activity concerned, would have the same skin wettedness (w) and heat exchange (H_{sk}) at skin surface as he would have in the actual test environment. Fig. 1 will now be the basis for this Standard Environment.

The definition of SET* now requires standardization of (a) clothing insulation worn in relation to activity, and (b) the effective heat transfer coefficients h'_s and h'_{es} for both clothing and effective air movement in Standard environment, such as those used to produce Fig. 1.

The proposed relation between standard activity (METS) and intrinsic clothing insulation (I_{cls}) is

$$I_{cls} = 1.33/(MET - WK + 0.74) - 0.095 \quad , \tag{13}$$

where MET and WK are in met units (1 met = 58.2 W/m²) and I_{cls} in clo units (1 Clo = 0.155 m²K/W). Other standardized properties for I_{cls} are 0.45 for its intrinsic permeation efficiency ratio i_{cl} and 0.25 for the factor k_{clo}, which describes the relative increase in the ratio f_{cls} of the clothed body surface (A_{cls}) to its skin surface (A_D) as $1 + 0.25 \times I_{cls}$.

Relative air movement for the Standard Environment is defined as the higher of the two convective heat transfer coefficients defined by

$$h_{cs} = 8.6\, V_s^{0.53};$$

where h_{cs} is never lower than a value V_s of 0.15 m/s for "still" air while resting. (14)

or by $$h_{cs} = 5.66\,(MET - 0.85)^{0.39} \quad . \tag{14'}$$

Equation (14') recognizes the fact that V_s increases with activity (MET).

Table 1 illustrates how the various standard heat transfer coefficients vary over the activity range from resting to 5 mets. It indicates the general validity of eq. (13) for standardizing clothing with activity at common SET* values (23°-24°) for "Comfort" as well for critical values of w at 0.85 and 1.0 in extreme heat.

Standard Operative Temperature (T_{so}) is defined as the uniform temperature of a still air enclosure in which the exchange of sensible (DRY) heat would be the same as in the test environment. Thus, by definition

$$DRY = h'(T_{sk} - T_o) = h'_s(T_{sk} - T_{so}) \qquad W/m^2 \tag{15}$$

or $$T_{so} = (h'/h'_s)\,T_o + (1 - h'/h'_s)T_{sk} \quad . \qquad °C \tag{15'}$$

Standard Operative vapor pressure is defined as the uniform vapor pressure P_{so} of a still air enclosure at T_{so}, in which the evaporative heat loss from the skin surface E_{sk} would be the same as in the test environment. Thus, by definition

$$E_{sk} = wh'_e(P_{ssk} - P_a) = wh'_{es}(P_{ssk} - P_{so}) \ , \qquad W/m^2 \tag{16}$$

or $$P_{so} = (h'_e/h'_{es})\,P_a + (1 - h'_s/h'_{es})P_{ssk} \quad . \qquad kPa \tag{16'}$$

The values for w, T_{sk} and P_{ssk}, observed in the test environment, also apply to the standard environment (SET*).

Finally, by definition SET* satisfies the heat balance equation

$$H_{sk} = h'_s(T_{sk} - SET^*) + wh'_{es}(P_{ssk} - 0.5P_{sSET}) \tag{17}$$

As was the case in eq. (5) above, SET* is the solution of

$$(T_{so} - SET^*) + (wh'_{es}/h'_s)(P_{so} - 0.5P_{sSET}) = 0 \quad . \tag{18}$$

The coordinates of Fig. 1, when used as a standard psychrometric chart, become T_{so} for T_o on ordinate and P_{so} for P_a on the abscissa. The ordinate and abscissa scale of Fig. 1 are applicable to a wide range of activities.

Whenever the Met-Clo relation (Eq. 13) is satisfied, the reader will recognize from Eq. (15) and (16), that, SET*, T_{so} and P_{so} also equal to ET*, T_o and P_a respectively for the test environment under consideration. Thus, the associated SET* or ET* may be evaluated visually from the Psychrometric chart (Fig. 1). Corresponding values of PMV* with ET* illustrated in Fig. 4 also apply.

When the Met-Clo relationship is not satisfied, T_{so} and P_{so} values for use in place of T_o and P_a in Fig. 1 must be evaluated analytically by using eq. (15) and (16). The value of SET* may be derived either as the solution of eq. (18), or as the solution of Eq. (1) and (17) by iteration without reference to T_{so} and P_{so}. PMV* for any Standard Environment may be evaluated now by replacing the DRY heat exchange term in Eq. 7 with $[h'_s(T_{sk}-SET^*)]$ and again without reference to T_{so}.

Our generalized definitions of PMV* and SET* are also valid towards cold temperatures, where insensible heat loss from skin surface is caused by E_{diff} and E_{comf}, as described in the Comfort Equation. When fully vasoconstricted, man's skin wettedness is less than 0.06 and SET* and T_{so} become essentially equal. A rise in metabolism due to shivering [15] would also cause a rise in T_{so} and SET*.

In the figures and examples to follow PMV* is the predicted sensory response of a subject to a hypothetical uniform environment at temperature SET* and 50% RH in which clothing worn is standardized for activity concerned (Eq. 13). By these definitions there is a consistent relationship between PMV* and SET* for a wide range of climatic conditions.

The reader is referred to Appendix B for a FORTRAN program which uses a 2-node model of human temperature regulation to calculate ET*, SET*, PMV, PMV*, T_{so}, and P_{so} from the basic observations of activity M, wk, T_a, T_o, P_a and their associated clothing transfer factors.

THE EFFECT OF AIR MOVEMENT, CLOTHING INSULATION AND ITS VAPOR PERMEABILITY ON PMV*

In the following four figures, we will demonstrate how the two key properties of clothing, i.e. its insulation and vapor permeability, affect thermal sensation and comfort as judged by the combined PMV* Index proposed above, as air movement and humidity are varied over the temperature range 0° - 45°C.

Figures 5 and 6 demonstrate the effect of changing levels of air movement and clothing insulation on comfort at two extremes of relative humidity - 15% RH and 85% RH. Whenever possible, activity and clothing insulation satisfy the eq. (13) criterion and in each of the figures to follow a SET* vs PMV* curve has been drawn for comparison. Both figures demonstrate our common experience that increasing air movement improves comfort at warm temperatures and increases discomfort in the cold. The opposite is true for increasing clothing insulation. Both Figures 5 and 6 show how lower relative humidity can greatly improve comfort in heat above 23° SET* but cause a sense of cold below 20° SET*.

Figures 7 and 8 demonstrate the importance of vapor permeability of the clothing worn on comfort. In both figures, the clothing insulation used satisfies the standard Clo-Met relation. An i_{cl} of 0.15 would describe a clothing assembly with high resistance to water vapor and perhaps with high coverage of the skin surface with clothing. An i_{cl} of 0.75 in contrast would describe a clothing assembly with low resistance to water vapor. Low vapor resistance may be accomplished either by use of light porous clothing or by greater exposure of skin surface or by both.

Figure 8 demonstrates the same relative roles of i_{cl} and humidity on PMV* in a slightly different light. Here humidity is described by three constant levels of P_a at 0.5, 1 and 2 kPa. Relative humidity as used in Figures 5, 6 and 7 tends to exaggerate its effect on "discomfort" in warm climates. The use of P_a curves instead of RH curves now increases the effect of vapor permeability i_{cl}. In cold, use of relative humidity is perhaps meaningless and the vapor pressure itself is the better humidity variable near saturation. In Figure 8 towards the cold, vapor pressure P_a has little effect on PMV*.

In general, both Fig. 7 and 8 show that in the zone of evaporative regulation (25° < SET* < ∿ 40°) both the vapor permeability of clothing used and the humidity of the actual environment play equally important roles in establishing comfort and thermal acceptability.

USE OF PMV* AND SET* AS INDICES OF HEAT STRESS

The example to be used is the case of natives, who work in the South Africa Gold Mines. For reasons of safety and prevention of fire and explosions, the mines must be operated at or near 100% RH. The natives work while virtually unclothed at activity levels averaging 3 mets which can be sustained for 2-3 hours without exhaustion in normal climates. Figure 9 indicates the three-way relationship between the ambient T_a at saturation (when $T_a = T_{dp}$), SET* and the predicted PMV* for this special work environment.

Wyndham [16], based on hundreds of observations of the behavior and heat tolerance of the mine workers, predicted the following limits:

(A) - Risks of heat stroke are negligible below 28.8°C (sat.).
(B) - A sharp rise in heat stroke occurs at 32.2° (sat.).
and (C) - A serious danger of fatality exists above 33.9° (sat.).

By comparing the limit (A) with the category descriptions on the ordinate, a PMV* of 0.5 or 29° SET* would serve as the upper limit for his acceptable working environment.
The threshold (B), for the start of serious risks of heat stroke, occurs at PMV* of 4 or 37.5° SET*, which value roughly coincides with the probable critical skin wettedness of 0.85 for maximum evaporative efficiency.

The limit (C), when PMV* ≈ 5 at 51.5° SET, falls in the zone, where skin blood flow from core to skin surface is maximal (90 $Lm^{-2}h^{-1}$); sweating occurs at 7-10 g/min and regulation of body temperature by evaporation of sweat has failed; and heart rate is over 200 bpm along with rapidly rising internal body temperature. Here there is only the question of the tolerance time possible to such extreme stress levels, such as would be measured by a Belding-Hatch Heat Stress Index level of 200 [17].

Comparison of PMV* with the proposed National Institute Occupational Safety and Health (NIOSH) limits [18] for heat stress at the same saturation conditions is possible. Their environmental measure is a temperature index WBGT found by a weighted average of the naturally ventilated wet bulb temperature, the ambient air temperature and a black globe thermometer. In a uniform saturated environment such as the African mines, WBGT would always equal the dry bulb. The WGBT Index was developed by Yaglou and Minard in 1957 as a practical field method of determining the old ASHVE ET [19].

The three limits proposed by NIOSH are:

(AL) - Alert Limit
(PEL) - Permissible Exposure Limit
(MEL) - Maximum Exposure Limit

The (AL) limit is well within our own PMV* range for comfortable and acceptable. (PEL) lies slightly below Wyndham's (A) limit for "zero risk". The (MEL) falls within the lower third of Wyndham's risk zone for heat stroke.

The general intent of PMV* or SET*, Wyndham's A, B and C temperature limits, and the NIOSH limits in terms of WBGT, all appear very much the same for the case of the gold miners.

A COMFORT-HUMIDITY CHART, BASED ON PMV*

In the current issue of the ASHRAE Handbook of Fundamentals (1985), - Fig. 13, Chapter 8, presented a Comfort-Humidity Chart based on heat strain as evidenced by skin wettedness, warm discomfort and heart rate, all of which are significantly affected by humidity. Figure 14 showed in contrast a Comfort-Humidity Chart in which temperature sensation (PMV), caused by heat load and skin temperature, is less affected by humidity. This same comparison was illustrated in Figs. 2 and 3 above. Since PMV* combines both the stress of the environment due to operative temperature and the thermo-regulatory strain due to skin wettedness, the Psychrometric Comfort-Humidity Chart for PMV* isotherms (Fig. 10) combines both interpretations.

Fig. 10 may be used in the following ways:

(1) By simply using the observed T_a and relative humidity or dew point temperature of the test environment, numerical values of PMV* and ET* may be predicted by interpolation,

(2) When T_a is unequal to T_o, i.e. radiant heat present, step (1) is plotted first. The appropriate PMV*^{a} is found by plotting the observed (T_o-T_a) either to the right or left of T_a paralleled to the abscissa; the new ET* and PMV* are interpolated as before in (1). If T_o was plotted directly, PMV* would be found by using an observed T_{dp} or ambient P_a instead of RH curves indicated on chart.

(3) SET* and Standard Operative Temperature T_{so} may be calculated analytically by eq. (1), (15) and (17) above for any environment in terms of the observed T_a or T_o and T_{dp} and the appropriate heat transfer coefficient (Vel, Clo, Met, etc.) associated with actual environment. A point, plotted on Fig. 10 on 50% RH curve for the calculated PMV* and for T_{so} on abscissa, would also indicate the corresponding standard operative vapor pressure P_{so} or equivalent standard dew point temperature (T_{dps}) on ordinate. By definition SET* = T_{so} on 50% RH locus.

(4) In general if M, Wk, Clo, i_{cl}, h', h'_{es}, T_o and T_{dp} or P_a in the test environment can be measured directly, only two of the four factors (PMV*, T_{so}, P_{sq} or T_{dps}) need be calculated to predict the other two from Fig. 10. When the ACT-CLOS relationship (eq. 13) is valid or assumed, T_o or T_a and one of the three humidity measurements (T_{dp}, P_a or RH) are needed to predict PMV* in Fig. 10 as drawn.

DISCUSSIONS AND CONCLUSIONS

Success of Fanger's PMV Index over the past 25 years has been the fact that it is based on the human heat balance equation and that all temperatures and heat transfer coefficients involved can be evaluated directly by HVAC engineers. The one term in the PMV equation that required evaluation experimentally over a wide range of conditions was the sensitivity coefficient α in equation (7).

The validity of warm discomfort as a linear function of skin wettedness has also stood the test of time. The concept "skin wettedness" is better understood by physiologists than engineers. As you will learn from my associates on the present program, it is now possible under certain test conditions to measure directly skin wettedness on the human body surface by simple physical instrumentation.

Since Fanger's PMV is based primarily in terms of heat load, its response by definition to changes in relative humidity or vapor pressure is minor. PMV is directly proportional to the operative temperature of the environment. PMV by definition is also insensitive to the vapor permeability of clothing worn. By redefining PMV* in terms of ET* or SET* instead of T_o, the new index PMV* is responsive to thermal stress caused by heat load, as well as to the physiological heat strain caused by changing humidity of the environment and by changing vapor permeability properties of clothing worn.

As seen in Figure 4, PMV* in contrast does have the same and even better responsiveness to changing humidity than DISC as defined here. PMV* is significantly responsive to the effect of humidity on Fanger's E_{comf} factor, when PMV=DISC=0, specially during light activity (2-3 met). At and above ET* or SET* temperatures that correspond to the w_{crit} limit of evaporative regulation, PMV* loci are parallel and reflect the heat stress caused by increasing rates of body heating.

The new PMV* has a second broad advantage over the original PMV as it is very responsive to changes in vapor permeation efficiency of the clothing worn. Figures 7 and 8 show clearly that the vapor permeation efficiency factor, i_{cl}, has an equally significant role in predicting comfort and discomfort as the ambient humidity.

Although the sensory factors underlying the definition of PMV and DISC have been recognized over the past 40 years as two distinct sensations with different physiological and sensory interpretations, the combined PMV* index can provide HVAC engineers with a new dimension to better understand human acceptability and performance over a wide range of thermal environments - whether hot or cold, dry or humid and clothed or unclothed.

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APPENDIX A

The combined heat and mass transfer coefficients as used in the heat balance equation.

Part A: The Sensible Heat Transfer Coefficient, h',

$$h' = 1/(I_a + I_{cl}) \quad , \quad Wm^{-2}K^{-1} \qquad A\text{-}1$$

where

$$I_a = 1/[f_{cl}(h_r + h_c)] \text{ or } 1/(f_{cl}h) \quad . \quad m^2K/W \qquad A\text{-}2$$

The linear radiation coefficient (h_r) varies from 4.55 at T_o = 20°C to 4.90 at T_o = 40°. The convective heat transfer coefficient h_c is given by 8.6 $V^{0.53}$, where V is ambient air movement in m/s or by 5.66 $(Met - 0.85)^{0.39}$, whichever is the larger is used in A-1 or A-2. Metabolism (Met) is expressed in met units (1 met = 58.2 Wm^{-2}).

I_{cl} is the intrinsic insulation of the clothing layer (equals 0.155 I_{clo}, when CLO units are used instead of m^2K/W for insulation). The factor f_{cl}, the ratio of the clothed body surface area A_{cl} to the body skin surface A_D, is given by $(1 + k_{clo}I_{clo})$. In the present analysis k_{clo} = 0.25 and constant.

Alternatively,

$$h' = f_{cl}hF_{cl}, \qquad A\text{-}3$$

where the Burton thermal efficiency factor, F_{cl} is

$$F_{cl} = 1/(1 + 0.155\, f_{cl}hI_{clo})$$

or

$$= I_a/(I_a + I_{cl}) \quad . \quad N.D. \qquad A\text{-}4$$

Part B: The Insensible Heat Transfer Coefficient h'_e.

Analogous to I_a and I_{cl} above, R_{ea} and R_{ecl} are the evaporative heat resistances of the "air" and "clothing" layers respectively, thus

$$h'_e = 1/(R_{ea} + R_{ecl}) \quad , \quad Wm^{-2}kPa^{-1} \qquad B\text{-}1$$

in which it is assumed the latent heat of evaporation occurs on the skin surface, and the passage of water vapor to the ambient environment is a function of the vapor resistance (R_{ea}) of the air and clothing layers (R_{ecl}).

The vapor heat resistance of the air and clothing layers are defined as

$$R_{ea} = 1/(L_a \cdot f_{cl} \cdot h_c) \qquad m^2.kPa/W \qquad B\text{-}2$$

or

$$= I_a/(L_a \cdot i_a) \qquad B\text{-}2'$$

where $i_a = h_c/h$ and $I_a = 1/(f_{cl} \cdot h_c)$ from A-2 above.

and

$$R_{ecl} = I_{cl}/(L_a \cdot i_{cl}) \quad . \quad m^2.kPa/W \qquad B\text{-}3$$

The factors i_a and i_{cl} (N.D.) above describe the permeation efficiency of water vapor through the air and clothing layers respectively. A typical value of i_{cl} for everyday clothing is 0.45. [9].

The factor L_a in B-2 is known as the "Lewis Relation" for air-vapor layer over skin surface and is defined as the ratio of the evaporative heat transfer coefficient h_e to the convective heat transfer coefficient h_c. L_a varies slightly with T_{sk} in K degrees and is given by

$$L_a = 15.15\,(T_{sk} + 273.2)/273.2 \quad . \quad K/kPa \qquad B\text{-}4$$

Alternatively

$$h'_e = L_a . i_m / (I_a + I_{cl}), \qquad \text{B-5}$$

where i_m is permeation efficiency ratio for the combined clothing and air layers, as used by Woodcock, Breckingbridge and Goldman [10].

The three permeation efficiency ratios, i_m, i_{cl}, and i_a, are related by

$$1/i_m = F_{cl}/i_a + (1 - F_{cl})/i_{cl} \qquad \text{N.D.} \qquad \text{B-6}$$

where

Burton's F_{cl} is defined in A-4 above.

From B-5;

$$i_m = (h'_e/h')/L_a \qquad \text{N.D.} \qquad \text{B-7}$$

and the negative slope of any ET* locus in Fig 1 is the product $w.L_a.i_m$.

Part C:

In the preceding sections, all heat transfer coefficients are expressed in terms of either $Wm^{-2}K^{-1}$ or $Wm^{-2}kPa^{-1}$. The (m^2) term always refers to the human Body Surface Area as measured by the DuBois Formula (see eq. 3, p. 8.2, ref. 4) as:

$$A_d = 0.202.(\text{weight in kg})^{0.425}.(\text{height in meters})^{0.725} \qquad \text{G-1}$$

The body surface area of an average sized man is considered here to be 1.8 square meters, with weight 70 kg and height 1.7 meters.

Part D: Conversion Factors - SI to IP

SI	Term	x Factor	IP
°C	temperature	x 1.8 + 32	F
K	absolute temperature	1.8	R
kg	mass	2.205	lb
m	length	3.281	ft
kJ	heat	0.9478	Btu
m^2	area	10.76	ft^2
kPa	pressure	0.1450	psi
W	power	3.412	Btu/hr
W/m^2	metabolism	0.3170	$Btu/hr.ft^2$
$W/(m^2.K)$	heat conductance heat transfer coef.	0.1761	$Btu/hr.ft^2.F$
$W/(m^2kPa)$	evap. mass transfer coef.	2.186	$Btu/hr.ft^2.psi$
K/kPa	Slope: Lewis Relation:ET* loci (Mollier Psychrometric Chart)	12.41	R/psi
kPa/K	Slope:ET* loci (Carrier Psychrometric Chart)	0.08058	psi/R

APPENDIX B

FORTRAN Program: Two Node Model of Human Temperature Regulation for Calculation of ASHRAE Comfort Indices

```
c-----------------------------------------------------------------------
c J.B.PIERCE : APG/APRF/LGB  (Prj.2NM/let27/rev.5/86)
c IBM PC-AT/DOS 3.10/PROFORT 1.00
c Computer program to evaluate the physiological and psychological
c response of human subjects to their thermal environment.
c The following members of the Pierce Lab. have made significant
c contributions to the present model over the past 20 years : Berglund,
c Casby, Fobelets, Gagge, Gonzales, Hardy, Nishi, Oohori, Stolwijk and
c many others as visiting fellows.
c -----------------------------------------------------------------------
c
c SIMULATION OF TEMPERATURE REGULATION.
c This routine simulates the temperature regulation over a 1 minute period
c Inputs are the physiological data from the previous time step and
c the current environmental conditions.
c Variables in common blocks let1 and let2 are defined prior to this
c routine.  Variables in common block let3 are defined in this routine
c
      subroutine letloop
      real lr,icl,icls,im,kclo
     0common /let1/ ttsk,ttcr,csw,cstr,cdil,bz,
     1skbfl,rgswl,act,we,vel,ienvir,clo,ata,evef,icl,im,
     2ta,rh,pa,erf,tr,chcc,kclo
     0common /let2/ alpha,eveff,rm,wk,tsk,tcr,tbm,
     1skbf,esk,chc,lr,chr,ff,facl,ctc,rclo,chclo,tcl,
     2cloe,fcle,fpcl,to,tski,tcri,alphai,skbfi,eski,sar
     0common /let3/ eres,cres,dry,
     1ttbm,dilat,stric,regsw,ersw,emax,rt,
     2edif,pwet,prsw,edrip,ediff,pdif,vpsk,rhsk
c
c------Dry heat balance : solve for TCL and CHR
 21   tclold=tcl
      chr=4.*.72*5.67e-8*((tcl+tr)/2+273.15)**3
      tcl=(chclo*tsk+facl*(chc*ta+chr*tr))/(chclo+facl*(chc+chr))
      if(abs(tcl-tclold).gt.0.01) goto 21
c
c------heat flow from clothing surface to environment (FACL=1. if CLOE used)
      dry=facl*(chc*(tcl-ta)+chr*(tcl-tr))
c
c------dry and latent respiratory heat losses
c------5.8662 kPa=44 mmHg; .017251=.0023*760 mmHg/101.325 kPa
      eres=.017251*rm*(5.8662-pa)
      cres=.0014*rm*(34.-ta)*ata*ff
c
c------Heat flows to skin and core : 5.28 is skin conductance in the
c------absence of skin blood flow
      hfsk=(tcr-tsk)*(5.28+1.163*skbf)-dry-esk
      hfcr=rm-(tcr-tsk)*(5.28+1.163*skbf)-cres-eres-wk
c
c------Thermal capacities (average man : 70 kg, 1.8 square meter)
      tccr=58.2*(1.-alpha)*70.
      tcsk=58.2*alpha*70
c
c------Temperature changes in 1 minute
      dtsk=(hfsk*1.8)/tcsk
      dtcr=(hfcr*1.8)/tccr
      dtbm=alpha*dtsk+(1.-alpha)*dtcr
      tsk=tsk+dtsk
      tcr=tcr+dtcr
c
```

```
c-----------------------------------------------------------------------
c-----Definition of vascular control signals----------------------------
c-----TTCR, TTSK, and TTBM are the set points for core, skin and--------
c-----average body temperatures corresponding to physiol. neutrality---
c-----BZ is the ratio of skin mass to total body mass (skin+core)------
c-----Typical values for TTCR, TTSK and BZ are 36.8, 33.7 and 0.10 ----
c-----ALPHA is the actual skin to total body mass ratio----------------
c-----------------------------------------------------------------------
      if(tsk.gt.ttsk) then
         warms=tsk-ttsk
         colds=0.
      else
         colds=ttsk-tsk
         warms=0.
      endif
      if(tcr.gt.ttcr) then
         warmc=tcr-ttcr
         coldc=0.
      else
         coldc=ttcr-tcr
         warmc=0.
      endif
      ttbm=bz*ttsk+(1.-bz)*ttcr
      tbm=alpha*tsk+(1.-alpha)*tcr
      if(tbm.gt.ttbm) then
         warmb=tbm-ttbm
         coldb=0.
      else
         coldb=ttbm-tbm
         warmb=0.
      endif
c
c-----------------------------------------------------------------------
c-----Physiological temperature regulation controls--------------------
c-----Constants for average/normal man : CDIL = 200 liters/(m2.hr.K)---
c-----                                   CSTR = 0.1 dimensionless------
c-----                                   CSW  = 170 g/(m2.hr)----------
c-----6.3 liter/(m2.hr) is normal SKBF---------------------------------
c-----in the absence of any thermoregulatory vascular control---------
c-----SKBFL = 90 liter/(m2.hr) = max SKBF------------------------------
c-----------------------------------------------------------------------
c-----control skin blood flow
      dilat=cdil*warmc
      stric=cstr*colds
      skbf=(6.3+dilat)/(1.+stric)
c
c-----SKBF is never below 0.5 liter/(m2.hr) nor above SKBFL
      if(skbf.lt.0.5) skbf=0.5
      if(skbf.gt.skbfl) skbf=skbfl
c
c-----ratio of skin-core masses change with SKBF
c-----(ALPHA,SKBF)=(.15,6.3),(.45,1.24),(.05,90)
      alpha=.0417737+.7451832/(skbf+.585417)
c
c-----control of regulatory sweating
      regsw=csw*warmb*exp(warms/10.7)
      if(regsw.gt.rgswl) regsw=rgswl
      ersw=.68*regsw
c-----adjustment of metabolic heat due to shivering (Stolwijk,Hardy)
      rm=act+19.4*colds*coldc
c
c-----------------------------------------------------------------------
c-----Evaluation of heat transfer by evaporation at skin surface-------
c-----------------------------------------------------------------------
c-----LR varies with TSK.
c-----LR=2.02 C/mmHg or 15.1512 C/kPa at 0 C  (lr=2.2 at 25 C)
      lr=15.1512*(tsk+273.15)/273.15
```

```
c-----Mass transfer equation between skin and environment
c-----RT is total vapor resistance of clothing + air layer
c-----IM is efficency of mass transfer for (clothing+air layer)
c-----ICL -     -     -     -          -     for clothing alone
c-----Reference : Woodcock, Breckenridge and Goldman
      rt=(1./im)*(1./(lr*facl*chc)+1./(lr*chclo*icl))
      emax=(1./rt)*(svp(tsk)-pa)
      prsw=ersw/emax
c
c-----.06 is PDIF for nonsweating skin --- Kerslake
      pdif=(1.-prsw)*.06
      edif=pdif*emax
      esk=ersw+edif
      pwet=esk/emax
c
c-----Beginning of dripping (Sweat not evaporated on skin surface)
      if((pwet.ge.eveff).and.(emax.ge.0.)) then
         pwet=eveff
         prsw=(eveff-.06)/.94
         ersw=prsw*emax
         pdif=(1.-prsw)*.06
         edif=pdif*emax
         esk=ersw+edif
      endif
c
c-----When EMAX<0. condensation on skin occurs.
      if(emax.lt.0.) then
         pdif=0.
         edif=0.
         esk=emax
         pwet=eveff
         prsw=eveff
         ersw=0.
      endif
c
c-----EDRIP = unevaporated sweat in grams/sq.m/hr
      edrip=(regsw*.68-prsw*emax)/0.68
      if(edrip.lt.0.) edrip=0.
c
c-----Vapor pressure at skin (as measured by dewpoint sensors)
      vpsk=pwet*svp(tsk)+(1.-pwet)*pa
c
c-----RHSK is skin relative humidity
      rhsk=vpsk/svp(tsk)
c
      return
      end
c-----Computation of comfort indices.  Inputs to this routine are the
c-----physiological data from the simulation of temperature regulation loop
c-----Variables in common blocks 1, 2 and 3 are defined prior to this
c-----routine.  Variables in block 4 are computed in this routine.
c
      subroutine letindex
      real lr,icl,icls,im,kclo,kclos
     0common /let1/ ttsk,ttcr,csw,cstr,cdil,bz,
     1skbfl,rgswl,act,we,vel,ienvir,clo,ata,evef,icl,im,
     2ta,rh,pa,erf,tr,chcc,kclo
     0common /let2/ alpha,eveff,rm,wk,tsk,tcr,tbm,
     1skbf,esk,chc,lr,chr,ff,facl,ctc,rclo,chclo,tcl,
     2cloe,fcle,fpcl,to,tski,tcri,alphai,skbfi,eski,sar
     0common /let3/ eres,cres,dry,
     1ttbm,dilat,stric,regsw,ersw,emax,rt,
     2edif,pwet,prsw,edrip,ediff,pdif,vpsk,rhsk
     0common /let4/ store,
     1set,et,pmv,pme,pms,hsi,
     2disc,tsens,sto,hr,efctc,efche,
     3slope,svpo,idc,xclo,xcloe,idd,xim,xicl
```

```
c-----------------------------------------------------------------------
c------Part I : Heat transfer indices in real environment---------------
c-----------------------------------------------------------------------
      ctc=chc+chr
      to=ta+erf/ctc
      cloe=clo-(facl-1.)/(.155*facl*ctc)
      fcle=1./(1.+.155*ctc*cloe)
      fpcl=1./(1.+(.155/icl)*chc*cloe)
c
c------clothing characteristics for printout (variable names start with x)
c------CLO = intrinsec clothing insulation, CLOE = effective cloth. insul.
c------Enter CLO and KCLO (compute CLOE) or enter CLOE and KCLO (compute CLO
c------Note : KCLO=0 --> CLO=CLOE,  KCLO>0 --> CLO>CLOE
c------Enter IM (compute ICL) or enter ICL (compute IM)
      xcloe=cloe
      if(idc.eq.1) then
         xclo=clo
      else
         xclo=1.-kclo*cloe-kclo/(.155*ctc)
         xclo=(-xclo+sqrt(xclo*xclo+4.*kclo*cloe))/(2.*kclo)
      endif
      if(idd.eq.1) then
         xicl=icl
         xim=(1./rt)*(1./(lr*facl*chc)+1./(lr*chclo))
      else
         xim=im
         xicl=facl*chc/(chclo*(rt*lr*facl*chc-1.))
      endif
c
c-----------------------------------------------------------------------
c------Part II : ET* (standardized humidity/real CLO ,ATA and CHC)-------
c-----------------------------------------------------------------------
c------calculation of skin heat loss (HSK)
      hsk=ctc*fcle*(tsk-to)+pwet*lr*chc*fpcl*(svp(tsk)-pa)
c
c------Get a low approximation for ET* and solve balance equation by iteration
      et=tsk-hsk/(ctc*fcle)
   90 err=hsk-ctc*fcle*(tsk-et)-pwet*lr*chc*fpcl*(svp(tsk)-svp(et)/2.)
      if(err.lt.0.) then
         et=et+.1
         goto 90
      endif
c
c-----------------------------------------------------------------------
c------Part III : Standard effective temperature SET*-------------------
c------standardized humidity. CHC, CLO, ATA normalized for given activity
c-----------------------------------------------------------------------
c------Standard environment
      chrs=chr
c
c------CHCS = standard conv. heat tr. coeff. (level walking/still air)
      chcs=5.66*(act/58.2-.85)**.39
c
c------minimum value of chc at sea level = 3.0 (vel=.137 m/s)
      if(chcs.lt.3.) chcs=3.
c
c------standard MET-CLOS relation gives SET*=24 C when PMV=0
      rn=rm-wk
      clos=1.3264/(rn/58.15+.7383)-.0953
      kclos=.25
      facls=1.+kclos*clos
      ctcs=chrs+chcs
      cloes=clos-(facls-1.)/(.155*facls*ctcs)
      fcles=1./(1.+.155*ctcs*cloes)
      fpcls=1./(1.+(.155/.45)*chcs*cloes)
```

```
c
c-----Get a low approximation for SET* and solve balance equ. by iteration
      set=tsk-hsk/(ctcs*fcles)
  200 err=hsk-ctcs*fcles*(tsk-set)-pwet*lr*chcs*fpcls*(svp(tsk)-.5*svp(set))
      if(err.lt.0.) then
         set=set+.1
         goto 200
      endif
c-----STO and SVPO are coordinates for standard environment
c-----STO = standard operative temperature
      sto=ctc*fcle/(ctcs*fcles)*to+(1.-ctc*fcle/(ctcs*fcles))*tsk
c
c-----SVPO = standard operative vapor pressure
      svpo=(chc*fpcl/(chcs*fpcls))*pat
     1 (1.-(chc*fpcl)/(chcs*fpcls))*svp(tsk)
c
c-----------------------------------------------------------------------
c-----Part IV : Fanger's comfort equation.  Predicted mean vote (PMV)--
c-----------------------------------------------------------------------
c-----ESW when >0, is evaporation by sweating only; when <0, ESW=-STORE
      esw=rn-cres-eres-ctc*fcle*(tsk-to)-edif
c
c-----Fanger's req. sweating at comfort threshold (PMV=0) is :
      ecomf=(rn-58.2)*.42
c
c-----PMV is the classic Fanger's index.
      pmv=(.303*exp(-.036*rm)+.028)*(esw-ecomf)
c
c-----PMV* (PME in prgm) uses ET instead of TO
      eswe=rn-cres-eres-ctcs*fcles*(tsk-et)-edif
      pme=(.303*exp(-.036*rm)+.028)*(eswe-ecomf)
c
c-----SPMV* (PMS in prgm) uses SET instead of TO
      esws=rn-cres-eres-ctcs*fcles*(tsk-set)-edif
      pms=(.303*exp(-.036*rm)+.028)*(esws-ecomf)
c-----SPMV* = PMV* in standard environment
c-----------------------------------------------------------------------
c-----Part V : Heat stress and heat strain indices derived from ESK,---
c-----EMAX, W (skin wettedness) and WCRIT-------------------------------
c-----------------------------------------------------------------------
c-----EMAX is readjusted for EVEFF and/or ECRIT
      emax=emax*eveff
c
c-----DISC (discomfort) varies with relative thermoregulatory strain
      disc=5.*(ersw-ecomf)/(emax-ecomf-edif)
c
c-----Belding's classic heat stress index (HSI)
      ereq=rn-cres-eres-ctc*fcle*(tsk-to)
      hsi=100.*ereq/emax
c
c-----Belding's HSI is also an index of thermoregulatory strain
c-----Heart rate (HR) is a fct of HSI and RM
c-----HR data base (Gonzales, 1968) as follows :
c-----(RM,HSI,HR)=(1,10,75),(1,100,110),(3,18,92),(3,100,170)
      if(hsi.le.0.) then
         hr=1.885*rm/58.2+69.225
      else
         hr=(.281*rm/58.2+.108)*hsi+1.885*rm/58.2+69.225
      endif
      if(hr.gt.220.) hr=220.
c
c-----------------------------------------------------------------------
c-----Part VI : Thermal sensation TSENS as function of mean body temp.-
c-----------------------------------------------------------------------
c-----TBML is TBM when DISC is 0.(lower limit of zone of evap. regul.)
      tbml=(.185/58.2)*rn+36.313
```

```
c
c-----TBML is TBM when HSI=100 (upper limit of zone of evap.regul.)
      tbmh=(.359/58.2)*rn+36.664
c
c-----TSENS=DISC=4.7 when HSI=100
c-----In cold, DISC & TSENS are the same and neg. fct of TBM
      if(tbm.gt.tbml) then
         tsens=4.7*(tbm-tbml)/(tbmh-tbml)
      else
         tsens=.68175*(tbm-tbml)
      endif
c
c----------------------------------------------------------------------
c-----Part VII : Other indices-----------------------------------------
c----------------------------------------------------------------------
c-----calculation of heat storage :
c-----Net metabolic rate - (respiratory heat loss) - (skin heat loss)
      store=(rm-wk)-(cres+eres)-(dry+esk)
c
c-----effective insensible heat tr. coeff. EFCHE in W/m2.kPa
      efche=lr*chc*fpcl
c

c-----effective sensible heat tr. coeff. EFCTC in W/m2.K
      efctc=ctc*fcle
c
c-----SLOPE on Mollier chart defines lines of const. enthalpy for the total
c-----humid environment including both clothing and air layer surrounding
c-----the body skin surface. SLOPE in K/kPa.(ta=ordinate,pa=abscissa)
      slope=pwet*efche/efctc
c
c-----Psychrometric ratio for total humid-clothing environment is :
c-----WCRIT*EFCHE/EFCTC or WCRIT*LA*IM
c
c-----losses shown as negative on printout
      ersw=-ersw
      edif=-edif
      eres=-eres
      cres=-cres
      dry=-dry
c
      return
      end
```

TABLE 1

Standard Transfer Coefficients and Critical SET^* Levels with Activity

Activity met (W/m^2)	I_{cls} Clo (1)	V_{eq} m/s (2)	h_{cs} $Wm^{-2}K^{-1}$ (3)	h_s $Wm^{-2}K^{-1}$ (4)	h'_s $Wm^{-2}K^{-1}$ (4)(5)	h'_{es} $Wm^{-2}kPa^{-1}$ (5)	h'_{es}/h'_s K/kPa (4)(5)	w_o at comfort N.D. (6)(7)	SET^*(slope) at comfort °C (K/kPa) (5)(6)	SET^*(slope) w_{crit}=0.85 °C (K/kPa) (6)	SET^*(slope) w_{crit}=1.0 °C (K/kPa) (6)
1 (58.2)	0.67	0.11	3.00	7.42	4.56	32.61	7.15	0.07	23.6(0.50)	38.9(5.96)	40.3(7.01)
1.25 (72.8)	0.57	0.23	3.96	8.38	5.18	40.77	7.87	0.10	23.8(0.79)	38.8(6.56)	40.6(7.72)
2 (115.4)	0.39	0.50	5.98	10.40	6.76	60.24	8.91	0.16	23.7(1.43)	39.2(7.42)	40.4(8.73)
3 (174.6)	0.26	0.80	7.61	12.09	8.48	81.52	9.61	0.20	23.6(1.92)	38.8(8.01)	39.6(9.42)
4 (232.8)	0.19	1.06	8.87	13.34	9.97	101.06	10.1	0.23	23.2(2.23)	37.0(8.45)	38.9(9.89)
5 (291.0)	0.14	1.30	9.88	14.36	11.31	119.55	10.6	0.28	22.4(2.97)	37.0(8.80)	38.4(10.4)

(1) by Eq. 13 for zero work; 1 Clo = 0.155 m^2K/W
(2) Equivalent air movement is $\exp[-0.79 + 0.74 \log_e(Met-0.85)]$
(3) Calculated by $5.66\ (met-0.85)^{0.39}$ (see Appendix B)
(4) All coefficients calculated for SET* at comfort
(5) for kclos=0.25; icls=0.45
(6) Slope is wh'e/h' at SET* values indicated for comfort, wcrit=0.85; and wcrit=1.0
(7) $w_o = (E_{comf} + E_{diff})/E_{max}$

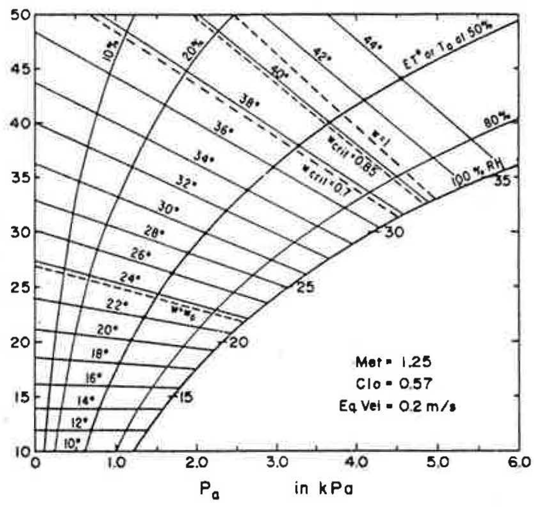

Figure 1. Mollier psychrometric chart of ET isotherms. See text for proper use with SET* isotherms*

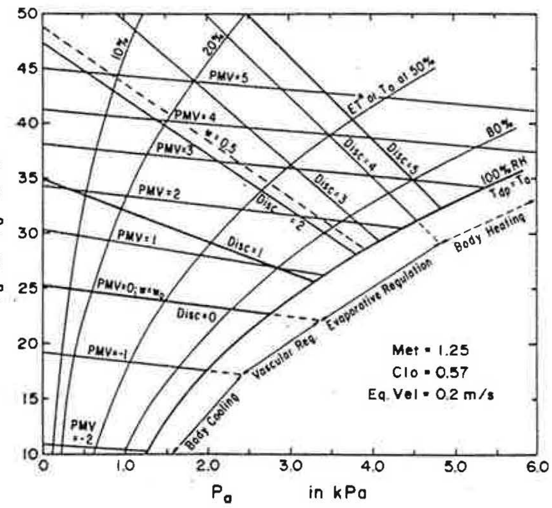

Figure 2. Isotherms for PMV and DISC on Mollier psychrometric chart

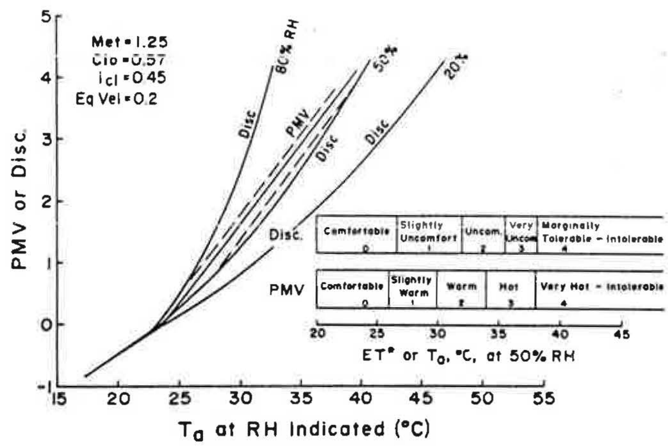

*Figure 3. Effect of relative humidity on PMV and DISC. Inset relates category scales for PMV and DISC with ET**

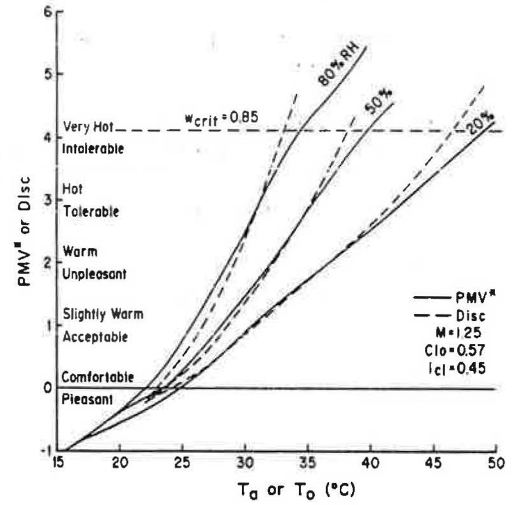

Figure 4. Effect of humidity on DISC and PMV, when PMV* is evaluated with ET* instead of T_o. Category scale suitable for both PMV* and DISC in warm climates is indicated on ordinate*

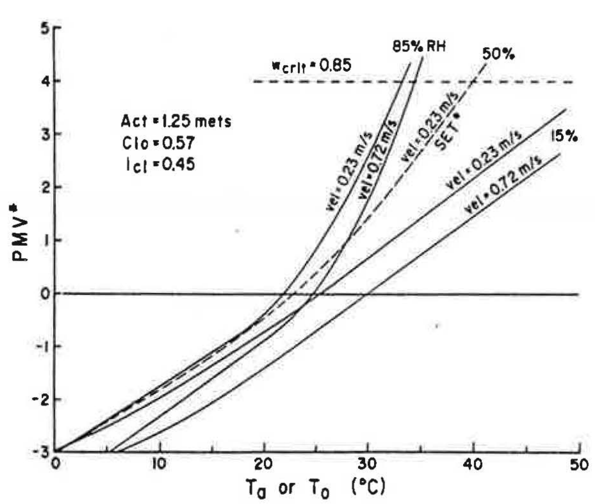

Figure 5. Effect of air movement on PMV at high and low relative humidity*

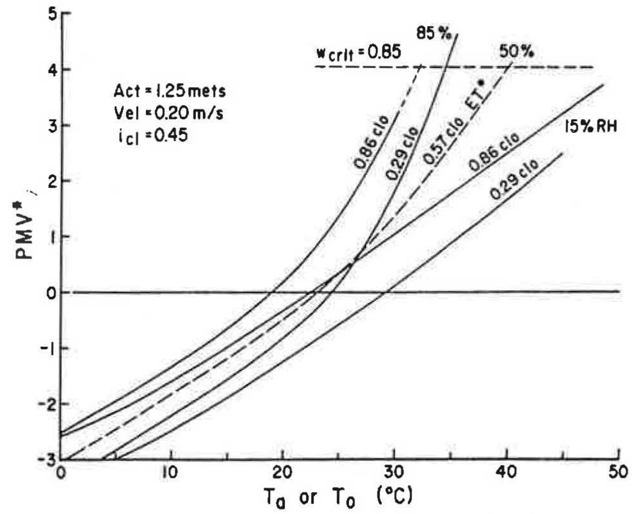

Figure 6. Effect of clothing insulation on PMV at high and low relative humidity*

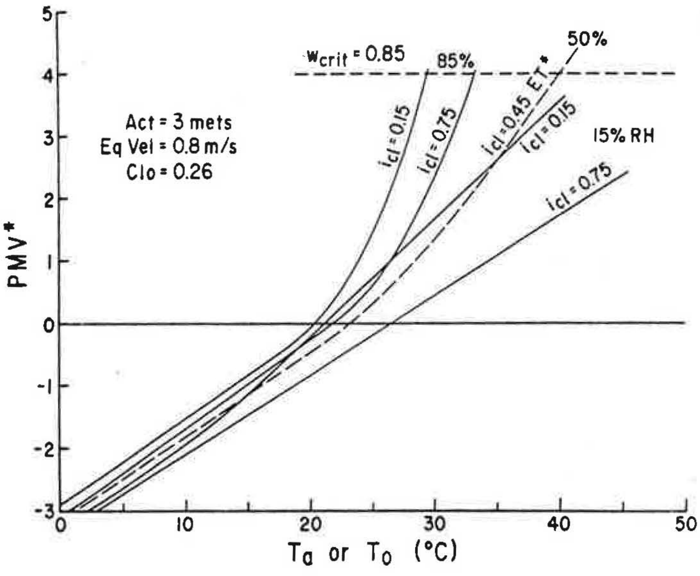

Figure 7. Effect of vapor permeability of clothing on PMV* at high and low relative humidity

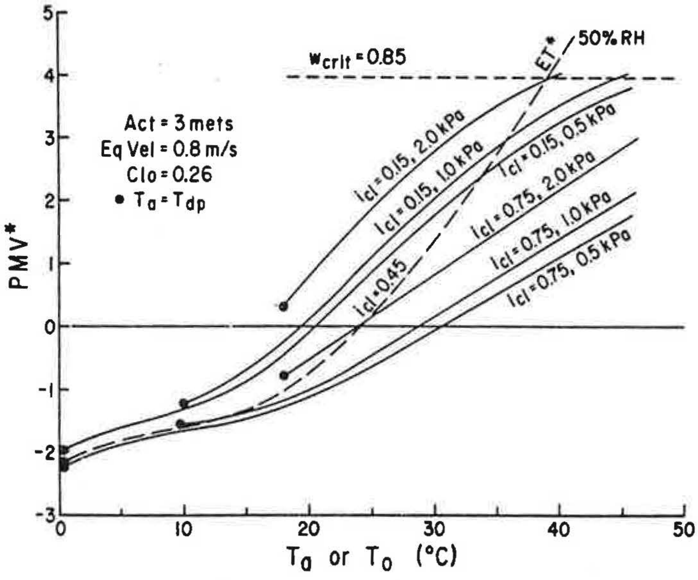

Figure 8. Effect of vapor permeability of clothing on PMV* at three levels of ambient vapor pressure

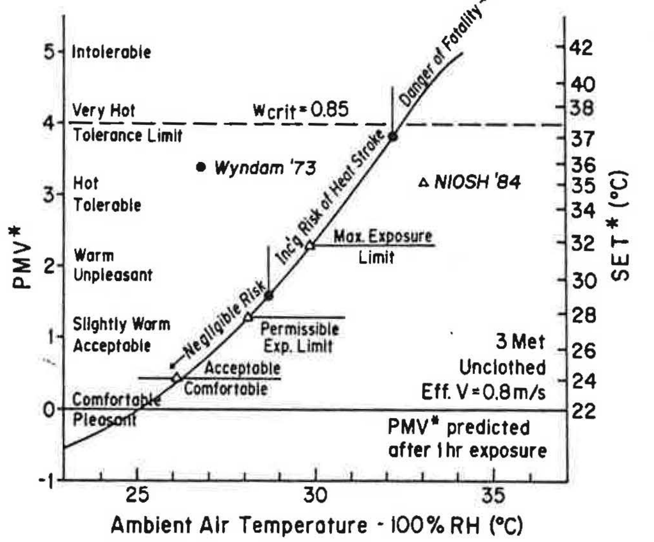

Figure 9. PMV* in saturated environments: comparison between suggested exposure limits by Wyndham (1973) and NIOSH (1984) for moderate exercise

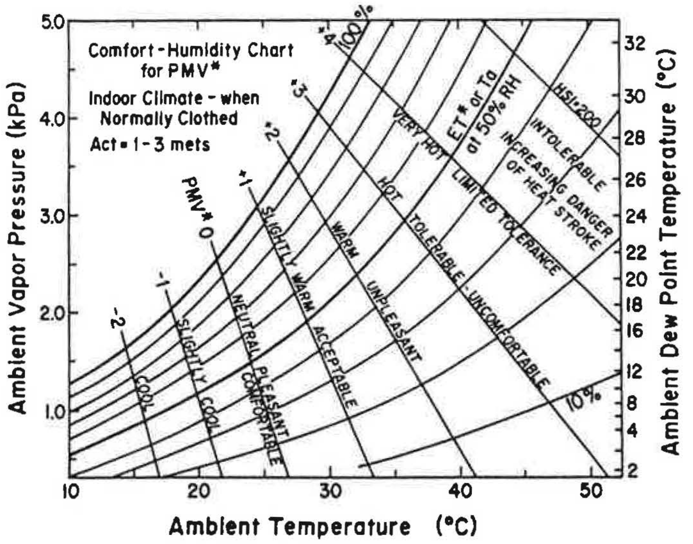

Figure 10. Comfort humidity chart for PMV* on Carrier psychrometric chart while normally clothed for 1-3 met activity in indoor climates

Discussion

R. GONZALES, U.S. Army Res. Inst. Env. Medicine, Natick, MA: In your last figure in the presentation (psychrometric chart) your lines of PMV are very similar to Yaglou's original old effective temperature iso-strain lines; although the old ET was not as rational as PMV, it's surprising that the old ASVHE does converge in the comfort zone. I would like to see a composite of all these "iso-strain" lines in the Fundamentals chapter just to clarify for the engineer where divergence exists.

A.P. GAGGE: The original ASHVE ET Comfort Chart was first published by Houghten and Yaglou in ASHVE Transactions (1923), Vol. 19, p. 151, and described responses of sedentary half-clothed subjects after they moved from one temperature-humidity condition to another. ET loci on a psychrometric chart described "Lines of Equal Comfort." Their first chart was criticized as being impractical (half-clothed) and unrealistic. Both Yaglou and Houghten soon published independently revised ET Charts for practical situations. We chose for the present comparison the revision by Houghten, Teague, and Miller, ASHVE Transactions (1926), Vol. 32, p. 185, for "lightly clothed subjects working in still air." Prof. Yaglou had moved in the meantime to Harvard University as an instructor at Prof. Drinker's School of Public Health, where he continued his studies with the early ET well into the postwar period.

In the figure attached, we have compared on a Mollier chart lines of Equal Comfort with PMV* loci, and ET* loci, as derived for 3 mets and 0.26 Clo. Comparison between the old ET and PMV* at 10^o again shows that the old ET would find the environment to be less cold than PMV* as relative humidity increases (i.e., steeper negative slope). At Comfort (PMV* = 0) and toward warm conditions, the difference between the negative slopes of the old ET and PMV* becomes insignificant. In the cold (10^o), as would be expected, the new ET* and w loci coincide. At Comfort (PMV* = 0), and throughout the zone of evaporative regulatiom, loci for ET* are always less steep than those for PMV*. However, at or near the W crit = 0.85 line, loci for the old ET, skin wettendess w, PMV*, and ET* all coincide.

We believe that after 60 years we may have succeeded finally in rationalizing the old ASHVE ET Charts in terms of the Human Heat Balance Equation, of all the heat and mass transfer coefficients involved for heat exchange by radiation, convection, and evaporation and by a new understanding of human temperature regulation during rest and exercise.

GONZALEZ: You mentioned in your presentation that the loci of constant PMV* in Figure 10 were also loci of constant wettedness. Since they were derived by substituting ET* (or SET*) for Operative Temperature in Fanger's Comfort Equation, are they loci of constant ET*?

A.P. FOBELETS and GAGGE: We believe that man senses both temperature and enthalpy of the total humid environment (which includes the clothing and air layers surrounding the skin surface). We believe the most representative index of temperature and enthalpy of the humid environment is ET* (or SET*). Wet-bulb temperature alone overestimates the effect of humidity. Operative temperature does not reflect the humidity content of the environment.

When we define PMV* by substituting ET* for To in Equation 7 in the text,

$$PMV^* = \alpha[H_{sk} - h'(T_{sk} - ET^*) - E_{diff} - E_{comf}]. \quad (7')$$

Wettedness, w, of the test environment is also defined in terms of ET* by solving for w in Equation 4:

$$w = [H_{sk} - h'(T_{sk} - ET^*)]/[h'_e(P_{ssk} - 0.5\ P_{sET})]. \quad (4')$$

The threshold wettedness, w_o, for Comfort in terms of ET* is given by Equation 12 in text as:

$$w_o = [E_{diff} + E_{comf}]/[h'_e(P_{ssk} - 0.5\ P_{sET^*})] \quad (12')$$

By substituting (4') and (12') in (7'),

$$PMV^* = [\alpha h'_e(P_{ssk} - 0.5\ P_{sET^*})](w - w_o) \quad (7'')$$

which demonstrates that PMV* is linear with skin wettedness. PMV*, like DISC, is a power function of ET*.

Finally, the threshold w_o, which includes Fanger's Ecomf factor, serves as a zero index for the PMV* sensory category scale and is neither a control factor in human temperature regulation nor a significant factor in the body heat balance equations, 1 and 2 above.

GAGGE, FOBELETS, and L.G. BERGLUND response to both questions: For the Zone of Evaporation Regulation:

1. Lines of "Equal Comfort" (i.e., the ET loci of Houghten, Yaglou, et al. in the 1923-26 period). of constant wettedness, of constant DISC, and of constant PMV*, all four fall into your class, "ISO-Strain" lines. Perhaps lines of constant heart rate may be also added.

2. The "Iso-Stress" lines are those for mean skin temperature, mean body temperature, and regulatory sweating, to which may be added Fanger's original PMV (see Figure 2).

3. ET* (or SET*) is a temperature measure of enthalpy of the total humid environment, which surrounds the wet skin surface and includes both the air and clothing layers. Wet-bulb temperature is a temperature measure of the enthalpy of the ambient environment itself.