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# EVALUATION OF THE PHYSIOLOGICAL BASES OF THERMAL COMFORT MODELS

**T.J. Doherty** **E. Arens, Ph.D.**
*ASHRAE Member*

## ABSTRACT

Thermal comfort models - specifically the J.B. Pierce two-node model of human thermoregulation and the Fanger Comfort Equation - predict comfort responses of individuals exposed to thermal environments under conditions of either rest or exercise. This paper evaluates the ability of these two models to predict the physiological variables underlying thermal comfort over a wide range of still air environments (effective temperature between 5°C and 45°C) and exercise intensities (rest to 85% of maximal aerobic capacity). The physiological data base used for comparison was taken from several published and as-yet unpublished studies at three different laboratories. Values of core temperature (TCR), skin temperature (TSK) and skin wettedness (w), predicted by the Pierce two-node model, and PMV, predicted by the Fanger model, differed significantly from observed values ($P<.05$). The Pierce model tended to underestimate w (mean error = -.16) and TCR (mean error = -.31°C), and to overpredict TSK (mean error = .48°C). Skin wettedness predictions were less accurate for high exercise intensity (6 to 8 met) than for rest, low exercise intensity (1 to 3.5 met) or moderate exercise intensity (3.5 to 6 met). Accuracy was higher for males than females, and greater for females in the follicular phase of the menstrual cycle than females in the luteal phase. Errors in TSK predictions were also associated with exercise intensity but not associated with either gender or effective temperature. TCR predictions were significantly more accurate for females than for males. The average error associated with PMV predictions was 1.26 scaling units and was related to both effective temperature ($ET^*$) and exercise intensity. Based on multiple linear regression with ET and exercise intensity, the expected error in PMV was approximately zero at ET=28°C for resting subjects. The magnitude of error increased by approximately .3 scaling units for each 1°C change in ET, and by approximately 1.3 scaling units for each increase in exercise intensity level (e.g. rest to low).

## INTRODUCTION

Occupant thermal comfort is one of the primary objectives of air heating, cooling, and conditioning systems. There are two readily available methods for determining the optimum combination of air temperature, humidity, and wind velocity for thermal comfort. These are ASHRAE Standard 55, based on standard effective temperature (SET) as calculated by the Pierce two-node model of human thermoregulation, and the ISO standard based on predicted mean vote (PMV) as calculated by the Fanger Comfort Equation and/or associated comfort charts. In addition to predicting thermal responses of individuals to office environments, the Pierce and Fanger models have been used in the past to predict responses to more extreme outdoor environments (Arens, Blyholder, and Schiller 1984, Arens and Bosselmann 1986, Arens, Berglund, and Gonzalez 1986), and to determine equivalent thermal environments for physiological testing (Gonzalez and Berglund 1978).

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Tammy J. Doherty, Graduate Student, Graduate Group in Bioengineering, University of California, Berkeley

Edward A. Arens, Professor, Department of Architecture, University of California, Berkeley

Internal body temperature and the physical properties of the skin surface are recognised as major factors affecting thermal discomfort and the temperature sensation caused by the environment. Both the Pierce and Fanger models predict physiological responses to the thermal environment and use these values to estimate thermal comfort. Estimation of physiological variables underlying thermal comfort and sensation requires the calculation of rates of heat exchange between the body and the surrounding environment. Several different factors may affect the accuracy of these calculations: (1) the coefficients for heat transfer are not known with certainty due to the complex shape of the body and the heterogeneity of body tissue; (2) the two primary modes of heat exchange, evaporation of sweat from the skin surface and convection of heat from internal sources to the skin, vary in an unknown manner with body temperature and psychological stress; (3) physical training state, state of heat or cold acclimation, relative proportions of lean and fat body mass, level of physical fitness and aerobic capacity, gender, age, and time of day are not accounted for in heat transfer equations.

Berglund (1978) tested the Pierce two-node model against experimental data for low exercise stress (30% of maximal aerobic capacity), warm and hot ambient temperatures (27°C to 50°C), and a wide range of relative humidities (20% to 80%). This validation showed a tendency for the model to overestimate skin temperature (TSK) and underestimate skin wettedness (w). A validation of a more complex 25-node model, incorporating basically the same empirical relationships as the Pierce model, found that for quasi-transient input conditions (ambient temperature or exercise intensity varying at 30- to 120-minute intervals), the model also tended to overpredict Tsk and underpredict w during exercise exposure simulations (Stolwijk 1971). While the PMV output of the Fanger model has been validated against measured thermal sensation judgements, we are unaware of any attempt to evaluate its accuracy based on physiological variables such as Tsk. Without a more comprehensive evaluation of these two models, their accuracy, especially at extreme input conditions is not known.

This paper will evaluate the ability of the Pierce and Fanger models to predict the physiological conditions underlying thermal comfort for both sedentary and exercising humans over a wide range of environmental conditions. An experimental data base was gathered from several published and as yet unpublished studies in which body temperature and skin wettedness were measured directly or calculated with good accuracy. This data base covers air temperatures between 10°C and 50°C, relative humidities between 20% and 80%, and exercise intensities from rest to 85% of maximal aerobic capacity. Each of the experiments included in the data base was performed at low air velocity and used minimally clothed, young, relatively fit test subjects. Averaged results for each experiment, along with a summary of the measuring techniques used to obtain the data, are given in Appendix A. Pierce model predictions are compared directly with observed values from the data base. Fanger's PMV is compared to the thermal sensation prediction curve based on skin temperature adjusted for metabolic rate given in Figure 1 (Berglund 1978).

## MODEL DESCRIPTIONS

The Pierce two-node model uses a finite difference procedure to estimate physiological parameters for any given thermal environment, subject metabolic rate and clothing insulation level. Geometrically, the body is modeled as two concentric cylinders, the inner cylinder representing the body core and the thin, outer cylinder representing the skin shell. The boundary line between the two nodes changes with respect to skin blood flow rate per unit skin surface area (SKBF, measured in $L/h \cdot m^2$) and is described by alpha - the fraction of total body mass attributed to the skin compartment:

$$\alpha = .0417737 + .7451832/(SKBF + .585417) \quad ,ND \qquad (1)$$

The body is represented by three temperatures, TSK for the skin shell, TCR for the core compartment, and a mean body temperature, TB, weighted by alpha. Thermoregulatory effector mechanisms (regulatory sweating, skin blood flow, and shivering) are defined in terms of thermal signals from the core (CRSIG), skin (SKSIG) and body (BSIG):

$$CRSIG = TCR - 36.8 \quad ,^{o}C \qquad (2)$$
$$SKSIG = TSK - 33.7 \quad ,^{o}C \qquad (3)$$
$$BSIG = TB - 36.49 \quad ,^{o}C \qquad (4)$$
$$SKBF = (6.3 + 200[CRSIG])/(1+.5[-SKSIG]) \quad ,L/m^2 \cdot h \qquad (5)$$

$$REGSW = 170[BSIG]\ e^{([SKSIG]/10.7)} \quad ,g/m^2 \cdot h \qquad (6)$$
$$MSHIV = 19.4[-CRSIG][-SKSIG] \quad ,W/m^2 \qquad (7)$$

where bracketed terms are set to zero if negative.

Physiological variables are updated at one minute intervals until the specified exposure time is reached. If the rates of body temperature change exceed 0.1 °C / min, timesteps of a fraction of a minute are used. Values of TCR, TSK, skin wettedness (w) and the rate of heat exchange between the skin and environment (MSK) are used to calculate effective temperature ($ET^*$) standard effective temperature (SET), thermal discomfort (DISC) and thermal sensation (TSENS).

The approach used in the Fanger model is entirely different from that of the Pierce model. Actual values of physiological parameters are not estimated. Instead, the skin temperature ($TSK_{REQ}$) and evaporative heat loss due to sweating ($ESW_{REQ}$) that would be required to achieve thermal comfort are estimated based on metabolic rate (M) in $W \cdot m^{-2}$:

$$TSK_{REQ} = 35.7 - .0275 \cdot M \quad ,^{\circ}C \qquad (8)$$
$$ESW_{REQ} = .42(M - 58.2) \quad ,W/m^2 \qquad (9)$$

These values are then used to calculate the body heat storage rate required for thermal comfort ($S_{REQ}$ in $W/m^2$) using equations presented below. An index of thermal sensation (PMV) is calculated based on $S_{REQ}$ (Equation 36).

In both models, a heat balance equation is the means for obtaining the physiological parameters underlying thermal comfort. The heat balance equation and equations for rates of heat transfer between the body and environment are basically the same for both models. A brief review of these equations is given below. More complete descriptions can be found in Fanger (1982) and Gagge et al. (1971, 1972, 1977, 1986).

The rate of heat stored by the body (S) is given as the rate of metabolic heat production (M) minus the heat energy lost to the environment through the skin and respiratory tract, and the mechanical energy lost due to work:

$$S = M - WK - ERES - CRES - RS - CS - ESK \quad ,W/m^2 \qquad (10)$$

where:
- ERES = rate of respiratory heat loss due to evaporation
- CRES = rate of respiratory heat loss due to convection
- ESK = rate of evaporative heat loss from the skin
- CS = rate of convective heat loss from the body surface
- RS = rate of radiant heat loss from the body surface
- M = metabolic rate
- WK = mechanical work rate
- S = rate of heat storage

Respiratory heat losses are estimated by the following equations (Fanger 1982):

$$ERES = .0023\ M\ (44 - PA) \quad ,W/m^2 \qquad (11)$$
$$CRES = .0014\ M\ (34 - TA) \quad ,W/m^2 \qquad (12)$$

where:
- TA is ambient temperature (°C)
- PA is ambient vapor pressure (Torr)

Radiant heat loss from the body surface is governed by the clothed body surface temperature (TCL) and mean radiant temperature (TR):

$$RS = .72\ f_{acl}\ \sigma \varepsilon\ ((TCL+273)^4 - (TR+273)^4) \quad ,W/m^2 \qquad (13)$$

where:
- TR is mean radiant temperature (°C)
- TCL is clothed body surface temperature (°C)
- .72 is the fractional body surface area exposed to thermal radiation (appropriate for seating, standing, supine positions)

$f_{acl}$ is the fractional increase in body surface attributed to clothing (approximated by $1+.968 \cdot ICL$, where ICL is intrinsic insulation of clothing in $m^2/W$)

$\sigma$ is the Stefan-Boltzmann constant ($5.67 \times 10^{-8}$ $W/m^2 \cdot K^4$)

$\mathcal{E}$ = skin emissivity (estimated by .97 in the Fanger model, 1.0 in the Pierce model)

In the Pierce model, RS is defined in terms of the difference between TCL and TR and a linearized radiant heat transfer coefficient ($h_r$):

$$RS = h_r \cdot f_{acl}(TCL - TR) \qquad ,W/m^2 \qquad (14)$$

and $$h_r = (4)(.72)\sigma\mathcal{E}\ ((TCL+TR)/2 + 273.15)^3 \qquad ,W/m^2 \cdot {}^oC \qquad (15)$$

Convective heat loss from the body varies linearly with the temperature difference between the ambient environment and the clothed body surface:

$$CS = h_c \cdot f_{acl}(TCL - TA) \qquad ,W/m^2 \qquad (16)$$

The linear heat transfer coefficient for convection ($h_c$) varies with the velocity of air movement around the body (v) in m/s and barometric pressure (PB) in Torr. The Pierce model uses the maximum value obtained from the following equations to represent $h_c$:

$$h_c = 3(PB/760)^{.53} \qquad ,W/m^2 \cdot {}^oC \qquad (17)$$
$$h_c = 8.6(v \cdot PB/760)^{.53} \qquad ,W/m^2 \cdot {}^oC \qquad (18)$$
$$h_c = 5.66(M/58.2 - .85)^{.39} \qquad ,W/m^2 \cdot {}^oC \qquad (19)$$

The maximum value obtained from the following equations is used to represent $h_c$ in the Fanger model:

$$h_c = 12.1(v)^{.5} \qquad ,W/m^2 \cdot {}^oC \qquad (20)$$
$$h_c = 2.38(TCL - TA)^{.25} \qquad ,W/m^2 \cdot {}^oC \qquad (21)$$

Each model uses a different means for estimating the temperature of the clothed body surface. The Fanger model uses an iterative solution to following equation:

$$TCL = TSK - ICL(RS + CS) \qquad ,{}^oC \qquad (22)$$

where:
ICL is clothing insulation ($m^2 \cdot {}^oC/W$).

In the Pierce model, TCL is estimated each iteration using the following equation:

$$TCL = (TSK/ICL + f_{acl}(h_c TA + h_r TR))/(1/ICL + f_{acl}(h_c + h_r)) \qquad ,{}^oC \qquad (23)$$

Total evaporative heat loss from the skin (ESK) includes evaporation of water produced by regulatory sweating (ESW) and evaporation of water vapor that diffuses through the skin surface (EDIF). In the Fanger model, ESK required for thermal comfort is given by the sum of $ESW_{REQ}$ and EDIF where:

$$EDIF = (.68)(.61)(PSK - PA) \qquad ,W/m^2 \qquad (24)$$

where:
.61 is the passive water vapor diffusion rate, ($g/h \cdot m^2 \cdot Torr$)
.68 is the latent heat of water, ($W \cdot h/g$)
Psk is the saturated water vapor pressure at $TSK_{REQ}$:
$= 1.92(TSK_{REQ}) - 25.3 \qquad ,Torr$

In the Pierce model, ESK is calculated from predictions of skin wettedness (w):

$$ESK = w\ h_e\ (PSK - PA) \qquad ,W/m^2 \qquad (25)$$

where:
$h_e = 2.2\ h_c/(1 + .92 \cdot ICL \cdot h_c) \qquad ,W/m^2 \cdot Torr \qquad (26)$
PSK is given by Antoine's equation: $= \exp(18.6686 - 4030.183/(TSK+235))$, (in Torr). (27)

Total skin wettedness includes wettedness due to regulatory sweating ($w_{SW}$) and diffusion through the skin ($w_{DIF}$). $w_{SW}$ is given by:

$$w_{SW} = .68 \cdot REGSW/EMAX \qquad ,ND \qquad (28)$$

where:
.68 is the latent heat of water (W·h/g).
EMAX is the rate of evaporative heat loss ($W/m^2$) when w=1 (calculated using Equation 25)

If $w_{SW}$ is greater than 1, one can assume a saturated skin surface and a certain amount of sweat dripping from the body that cannot be evaporated. In this case w is set equal to 1 and ESK is set equal to EMAX. When $w_{SW}$ is less than one, the fraction of body surface wet due to diffused water vapor is assumed to be 6% of the dry skin area:

$$w_{DIF} = .06(1 - w_{SW}) \qquad ,ND \qquad (29)$$

*In this case, total skin wettedness is the sum of* $w_{DIF}$ *with* $w_{SW}$ *and ESK is determined by* Equation 25.

The Pierce model requires one additional heat flow term describing the heat transfer between the internal core compartment and the outer skin shell:

$$HF_{c-s} = (5.28 + 1.163 \cdot SKBF)(TCR - TSK) \qquad ,W/m^2 \qquad (30)$$

where:
1.163 is the thermal capacity of blood (W·h/L·°C)
5.28 is the average body tissue conductance ($W/m^2 \cdot °C$)

Individual heat balance equations for core and skin compartments are expressed using $HF_{c-s}$:

$$SSK = HF_{c-s} - ESK - RSK - CSK \qquad ,W/m^2 \qquad (31)$$
$$SCR = M - WK - ERES - CRES - HF_{c-s} \qquad ,W/m^2 \qquad (32)$$

New temperatures are calculated each iteration from rates of heat storage in the core and skin:

$$TCR = TCR + SCR \cdot A_D/(.97(1-\alpha)Wt) \qquad ,°C \qquad (33)$$
$$TSK = TSK + SSK \cdot A_D/(.97\alpha \cdot Wt) \qquad ,°C \qquad (34)$$
$$TB = TSK + (1-\alpha)TCR \qquad ,°C \qquad (35)$$

where
.97 is the thermal capacitance of body tissue (W·h/kg·°C)
Wt is body weight (kg)
$A_D$ is body surface area calculated by the Dubois Equation
$= .203 \cdot Ht^{.725} \cdot Wt^{.425}$ ($m^2$), Ht is height in meters

Calculation of TSENS, PMV, and DISC is based on the above heat transfer calculations. An 11-point psychophysical scale is used to describe TSENS and PMV: intolerably cold (-5), very cold (-4), cold (-3), cool (-2), slightly cool (-1), neutral (0), slightly warm (+1), warm (+2), hot (+3), very hot (+4), intolerably hot (+5). DISC can be either positive or negative, negative values representing cold discomfort and positive values representing warm discomfort. Numerically, DISC is described as: comfortable and pleasant (0), slightly uncomfortable but acceptable (1), uncomfortable and unpleasant (2), very uncomfortable (3), limited tolerance (4), and intolerable (5).

PMV is calculated based on M and $S_{REQ}$:

$$PMV = (.303\, e^{(-.036\, M)} + .276)\, S_{REQ} \qquad (36)$$

TSENS is defined in terms of mean body temperature. Thermal discomfort is numerically equal to TSENS when TB is below some setpoint ($TB_C$) and is related to skin wettedness when body temperature is regulated by sweating:

$$TB_C = (.194/58.15)(M-WK) + 36.301 \qquad ,°C \qquad (37)$$
$$TB_H = (.347/58.15)(M-WK) + 36.669 \qquad ,°C \qquad (38)$$
$$TSENS^C = .4685(TB - TB_C) \qquad (39)$$

$TSENS^W = (4.7)ev_{eff}(TB - TB_C)/(TB_H - TB_C)$ (40)
$TSENS^H = (4.7)ev_{eff} + .4685(TB - TB_H)$ (41)
$DISC^C = .4685(TB - TB_C)$ (42)
$DISC^W = 4.7(ESW - ESW_{REQ})/(EMAX - ESW_{REQ} - EDIF)$ (43)

where:

$ev_{eff}$ is evaporative efficiency (assumed to be .85)

The superscript C refers to $TB<TB_C$, W refers to $TB_C<TB<TB_H$, H refers to $TB>TB_H$.

## MODEL EVALUATIONS

The experimental data set was classified according to exercise intensity, where "rest" corresponded to zero physical work, "low" corresponded to exercise intensities less than 50% of maximal aerobic capacity (approximately 58 to 204 $W/m^2$), "moderate" corresponded to intensities between 50% and 75% of maximal aerobic capacity (approximately 204 to 350 $W/m^2$), inclusive, and "high" corresponded to intensities greater than 75% of maximal aerobic capacity (approximately 350 to 470 $W/m^2$). The data were also classified according to gender, m representing males, ff representing females in the follicular phase of the menstrual cycle, and fl representing females in the luteal phase. Any woman whose menstrual cycle phase was not recorded was assumed to be follicular.

Values of TCR, TSK and w, predicted by the Pierce two-node model, and PMV, predicted by the Fanger model, were compared to corresponding experimental observations and found to differ significantly ($P<.05$). A summary of paired analyses are presented in Table 1. Partial correlation analysis and analysis of covariance were used to determine the association between model accuracy and the ambient environment (represented by effective temperature), exercise intensity, and gender. A .05 significance level was used for all tests. Whenever a significant F ratio was observed, Tukey's critical difference procedure ($P<.05$) was used to determine where differences existed. Results of the analyses of covariance are given in Table 2.

In general, the Pierce model tended to underestimate skin wettedness and core temperature, and to overpredict skin temperature. These results agree with previous evaluations by Berglund (1978) and Stolwijk (1971). In addition, magnitudes of error were found to be associated with both gender and exercise intensity, but not with effective temperature.

Skin wettedness predictions were significantly less accurate for high exercise intensity than for rest, low exercise intensity or moderate exercise intensity. Accuracy was higher for males than females, and greater for females in the follicular phase of the menstrual cycle than females in the luteal phase. Plots of w observed and predicted versus effective temperature for four different activity levels are given in Figures 2-5.

The accuracy of skin temperature predictions was influenced by exercise intensity but not associated with either gender or effective temperature. In general, higher exercise intensities were associated with greater inaccuracy. The average difference between TSK observed and TSK predicted was close to zero for resting exposure, approximately 0.4°C for low exercise intensity, and greater than 0.9°C for moderate to high exercise intensity. Plots of Tsk observed and predicted against effective temperature for four different activity levels are shown in Figures 6-9.

Core temperature predictions underestimated observed values by an average of 0.31°C. Accuracy was significantly greater for females than for males. Errors associated with TCR predictions were not significantly influenced by either effective temperature or exercise intensity.

Although Pierce model predictions of TCR, TSK and w were significantly different from observed values, it is more interesting, for thermal comfort purposes, to look at whether these differences represent significant errors in predictions of thermal comfort indices. Partial differentiation of the DISC and TSENS equations (39-43) was performed to determine the relative contributions of TCR, TSK, and w to these variables. When $TB<TB_C$, average error for both TSENS and DISC is .939 (+/- 1.269) scaling units for each °C error in TCR, and .266 (+/- .269) scaling units for each °C error in TSK. When $TB>TB_C$, the average error in DISC for an error in skin wettedness of .1 is .585 (+/- .077) scaling units. When $TB_C<TB<TB_H$, TSENS was highly

sensitive to errors in both TCR and TSK. The average error for a $1^{\circ}C$ error in TCR was 11.498 (+/- 4.484) scaling units. Expected error based on TSK was .846 (+/-.494) scaling units per $^{\circ}C$. Finally, in extremely hot conditions ($TB>TB_H$) the average errors for TSENS were .471 (+/- .018) scaling units for each $^{\circ}C$ error in TCR and .026 (+/- .010) scaling units for each $^{\circ}C$ error in TSK. These results suggest that when body temperature is low, the observed errors in TCR, TSK, and w correspond to relatively insignificant errors in TSENS and DISC. For exercise simulations, large errors in physiological variables and increased sensitivity of TSENS and DISC to TCR, TSK, and w result in large expected errors in TSENS and DISC.

Two possible sources of error in the Pierce model are the empirical equations for sweat rate and skin blood flow. Although the control coefficients (e.g. 170 for REGSW) can vary by as much as 50% without significantly changing thermal equilibrium values, they do affect time to equilibrium (Gagge et al. 1972). During severe thermal stress, when thermal equilibrium is not reached during the exposure, the time to equilibrium and hence the effect of these control coefficients is more important. Figure 10 shows observed sweating rate versus an integrated thermal signal (TSIG) defined according to the Pierce model:

$$TSIG = [BSIG] \exp([SKSIG]/10.7)$$

where the alpha underlying BSIG is set at .11. In this figure, the solid line represents the Pierce model prediction (Equation 6) given observed core and skin temperatures. Although the Pierce model is fairly accurate at rest and low exercise intensity, it severely underestimates observed values of Esw at moderate and high exercise levels, possibly leading to the underestimation of skin wettedness and overestimation of TSK.

Figure 11 shows observed values of skin blood flow versus core temperature when the thermal signal responsible for vasoconstriction [-SKSIG] is zero. The solid line represents the corresponding Pierce model prediction (Equation 5) of SKBF given observed values of core temperature. In general the Pierce model overestimates skin blood flow due to active vasodilation, possibly contributing to the overestimation of TSK.

The accuracy of the Fanger model was determined by comparing PMV with thermal sensation (Tsens) calculated according to observed values of Tsk adjusted for metabolic rate (Berglund 1978) as in Figure 1. In general, the model tended to overpredict the thermal sensation response (mean error = 1.29 scaling units). A plot of PMV and thermal sensation against effective temperature is shown in Figure 12. The error associated with PMV predictions was related to both effective temperature and exercise intensity. Based on a multiple linear regression with ET and exercise intensity, the expected error in PMV was approximately zero at $ET=28^{\circ}C$ for resting subjects. The magnitude of error increased by approximately .3 scaling units for each $1^{\circ}C$ change in ET, and by approximately 1.3 scaling units for each increase in exercise intensity level (e.g. rest to low).

## SUMMARY

From the analyses presented in the previous section, it is clear that the Pierce model is accurate for simulations of resting humans but relatively inaccurate for exercise simulations. The exercise intensities used in these evaluations were severe as compared with normal office routine and no conclusions can be made as to the accuracy of the model for light exercise normally encountered in the office environment (walking, light lifting etc.). Accuracy was not affected by effective temperature, validating its use over a wide range of environments for sedentary humans. The effects of high wind velocity, thermal radiation, clothing insulation and subject age on model accuracy was not studied. There is some indication that gender and perhaps female menstrual cycle phase affect model accuracy, but because of the small number of observations for luteal females, this effect is questionable.

The accuracy of the Fanger model is good for simulations of resting subjects but decreases as exercise intensity increases. Accuracy is also affected by effective temperature and is greatest when $26^{\circ}C<ET<30^{\circ}C$. Outside this range, errors in PMV predictions are expected to exceed .5 scaling units. Gender did not significantly affect the accuracy of the Fanger model.

It might be mentioned that although an attempt was made to balance the experimental data base, some skewness did occur. For example, observations for luteal females occured only in warm and hot environments. In addition, there were fewer observations corresponding to high exercise intensity than rest, low exercise intensity, or moderate exercise intensity.

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## APPENDIX

### Summary of Observed Environmental and Physiological Parameters

The following table summarizes the experimental procedures and conditions of the data base used in this paper. Core temperature was estimated either by esophageal or rectal temperature. Mean skin temperature was estimated from local skin temperature measurements at six, eight or ten sites. The rate of total body water loss was either measured directly using a Potter balance or estimated from total body weight loss distributed in time according to local sweating rates, measured using dew point capsules positioned on the skin surface. Each line in the table represents exposure to a single environment and exercise intensity. Gonzalez[3] and Stolwijk (1971) conducted transient experiments in which the subjects were exposed to more than one environment or exercise intensity per session.

| n | Wt | $A_D$ | Ta | Pa | clo | M | Wk | TIME | Tcr | Tsk | Esk |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Gonzalez 1981[1] | | | | | | | | | | | |
| 6f | 55.6 | 1.6 | 18 | 7 | .15 | 348 | 49 | 35 | $38.0^e$ | $29.0^8$ | $89^P$ |
| 6f | 55.6 | 1.6 | 35 | 10 | .15 | 352 | 63 | 35 | $38.0^e$ | $34.3^8$ | $167^P$ |
| Stephenson 1982[2] | | | | | | | | | | | |
| 4f | 58.7 | 1.7 | 35 | 15 | .15 | 314 | 61 | 30 | $37.8^e$ | $35.0^8$ | $353^T$ |
| 41 | 58.7 | 1.7 | 35 | 15 | .15 | 297 | 60 | 30 | $38.0^e$ | $35.1^8$ | $462^T$ |
| Gonzalez and Berglund 1978 | | | | | | | | | | | |
| 5m | 74.0 | 1.9 | 50 | 30 | .05 | 177 | 33 | 40 | $38.7^e$ | $37.9^8$ | $266^P$ |
| 5m | 74.0 | 1.9 | 50 | 30 | .05 | 177 | 33 | 40 | $38.5^e$ | $37.6^8$ | $305^P$ |
| 5m | 74.0 | 1.9 | 45 | 33 | .05 | 177 | 33 | 40 | $38.4^e$ | $37.3^8$ | $242^P$ |
| 5m | 74.0 | 1.9 | 41 | 35 | .05 | 177 | 33 | 40 | $38.2^e$ | $37.0^8$ | $180^P$ |
| 5m | 74.0 | 1.9 | 35 | 38 | .05 | 177 | 33 | 40 | $38.2^e$ | $36.6^8$ | $135^P$ |
| 5m | 74.0 | 1.9 | 42 | 26 | .05 | 177 | 33 | 40 | $38.0^e$ | $36.4^8$ | $211^P$ |
| 5m | 74.0 | 1.9 | 38 | 30 | .05 | 177 | 33 | 40 | $38.0^e$ | $36.0^8$ | $156^P$ |
| 5m | 74.0 | 1.9 | 34 | 35 | .05 | 177 | 33 | 40 | $38.0^e$ | $35.9^8$ | $120^P$ |
| 5m | 74.0 | 1.9 | 40 | 18 | .05 | 177 | 33 | 40 | $37.8^e$ | $35.5^8$ | $171^P$ |
| 5m | 74.0 | 1.9 | 35 | 25 | .05 | 177 | 33 | 40 | $37.8^e$ | $34.8^8$ | $136^P$ |
| 5m | 74.0 | 1.9 | 32 | 30 | .05 | 177 | 33 | 40 | $37.9^e$ | $34.5^8$ | $112^P$ |
| 5m | 74.0 | 1.9 | 34 | 15 | .05 | 177 | 33 | 40 | $37.5^e$ | $34.0^8$ | $136^P$ |
| 5m | 74.0 | 1.9 | 32 | 20 | .05 | 177 | 33 | 40 | $37.4^e$ | $33.6^8$ | $119^P$ |
| 5m | 74.0 | 1.9 | 30 | 25 | .05 | 177 | 33 | 40 | $37.9^e$ | $33.6^8$ | $100^P$ |
| 5m | 74.0 | 1.9 | 28 | 13 | .05 | 177 | 33 | 40 | $37.4^e$ | $32.3^8$ | $91^P$ |
| 5m | 74.0 | 1.9 | 26 | 19 | .05 | 177 | 33 | 40 | $37.4^e$ | $31.9^8$ | $70^P$ |
| Gonzalez et al. 1983[3] | | | | | | | | | | | |
| 4m | 74.6 | 1.9 | 20 | 7 | .15 | 51 | 0 | 20 | $36.4^e$ | $31.1^8$ | $28^T$ |
| | | | 20 | 7 | .15 | 202 | 30 | 35 | $36.9^e$ | $30.9^8$ | $72^T$ |
| 4m | 74.6 | 1.9 | 30 | 8 | .15 | 50 | 0 | 20 | $36.6^e$ | $34.6^8$ | $54^T$ |
| | | | 30 | 8 | .15 | 204 | 30 | 35 | $37.0^e$ | $34.4^8$ | $190^T$ |
| 4m | 74.6 | 1.9 | 20 | 7 | .15 | 48 | 0 | 20 | $36.5^e$ | $31.5^8$ | $47^T$ |
| | | | 20 | 7 | .15 | 316 | 64 | 35 | $37.2^e$ | $31.5^8$ | $166^T$ |
| 4m | 74.6 | 1.9 | 30 | 7 | .15 | 52 | 0 | 20 | $36.6^e$ | $34.8^8$ | $72^T$ |
| | | | 30 | 7 | .15 | 330 | 64 | 35 | $37.5^e$ | $34.5^8$ | $298^T$ |
| 5f | 59.3 | 1.7 | 20 | 8 | .15 | 54 | 0 | 20 | $36.8^e$ | $31.6^8$ | $25^T$ |
| | | | 20 | 8 | .15 | 191 | 22 | 35 | $37.2^e$ | $31.4^8$ | $78^T$ |
| 5f | 59.3 | 1.7 | 30 | 8 | .15 | 52 | 0 | 20 | $36.7^e$ | $34.4^8$ | $56^T$ |
| | | | 30 | 8 | .15 | 170 | 22 | 35 | $37.0^e$ | $34.2^8$ | $127^T$ |
| 5f | 59.3 | 1.7 | 20 | 7 | .15 | 51 | 0 | 20 | $36.7^e$ | $31.1^8$ | $31^T$ |
| | | | 20 | 7 | .15 | 274 | 47 | 35 | $37.2^e$ | $30.9^8$ | $273^T$ |
| 5f | 59.3 | 1.7 | 30 | 12 | .15 | 41 | 0 | 20 | $36.8^e$ | $34.9^8$ | $87^T$ |
| | | | 30 | 12 | .15 | 284 | 47 | 35 | $37.5^e$ | $34.6^8$ | $258^T$ |

**KEY**

- e Esophageal temperature
- r Rectal temperature
- 6 6 site mean Tsk calculation
- 8 8 site " "
- 10 10 site " "
- p Potter balance
- t Total body weight loss, distributed in time according to local sweating rates.
- n No active regulatory sweating

1 Gonzalez, R.R. 1981. Unpublished study titled "Forearm blood flow and sweating in trained and untrained females." J.B. Pierce Institute., New Haven, CT.

2 Stephenson, L.A. 1982. Unpublished study titled "Forearm blood flow and local sweating modulations during the human menstrual cycle.", J.B. Pierce Institute.

3 Gonzalez, R.R., Stephenson, L.A. and Kolka, M.A. 1983. Unpub. study: "Forearm blood flow and local sweating for exercising humans at sea level and hypobarics." USARIEM, Natick MA.

| n | Wt | $A_D$ | Ta | Pa | clo | M | Wk | TIME | Tcr | Tsk | Esk |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Stolwijk 1971 | | | | | | | | | | | |
| m | 74.1 | 1.9 | 30 | 10 | .05 | 47 | 0 | 30 | $37.3^r$ | $33.8^{10}$ | $24^P$ |
| | | | 48 | 25 | .05 | 47 | 0 | 120 | $37.9^r$ | $36.7^{10}$ | $124^P$ |
| | | | 30 | 10 | .05 | 47 | 0 | 60 | $37.6^r$ | $34.0^{10}$ | $26^P$ |
| m | 74.1 | 1.9 | 43 | 19 | .05 | 47 | 0 | 60 | $37.3^r$ | $35.7^{10}$ | $93^P$ |
| | | | 17 | 4 | .05 | 47 | 0 | 120 | $36.9^r$ | $28.4^{10}$ | $8^P$ |
| | | | 43 | 19 | .05 | 47 | 0 | 30 | $36.7^r$ | $35.7^{10}$ | $27^P$ |
| m | 74.1 | 1.9 | 30 | 10 | .05 | 46 | 0 | 30 | $37.1^r$ | $33.3^{10}$ | $29^P$ |
| | | | 30 | 10 | .05 | 144 | 22 | 30 | $37.3^r$ | $33.3^{10}$ | $135^P$ |
| | | | 30 | 10 | .05 | 46 | 0 | 30 | $37.1^r$ | $33.2^{10}$ | $40^P$ |
| | | | 30 | 10 | .05 | 260 | 47 | 30 | $37.7^r$ | $33.9^{10}$ | $190^P$ |
| | | | 30 | 10 | .05 | 46 | 0 | 30 | $37.3^r$ | $33.0^{10}$ | $36^P$ |
| | | | 30 | 10 | .05 | 431 | 85 | 30 | $38.5^r$ | $34.0^{10}$ | $306^P$ |
| | | | 30 | 10 | .05 | 46 | 0 | 30 | $38.0^r$ | $33.3^{10}$ | $65^P$ |
| m | 74.1 | 1.9 | 20 | 5 | .05 | 46 | 0 | 30 | $37.1^r$ | $28.9^{10}$ | $9^P$ |
| | | | 20 | 5 | .05 | 145 | 22 | 30 | $37.2^r$ | $29.7^{10}$ | $9^P$ |
| | | | 20 | 5 | .05 | 46 | 0 | 30 | $37.1^r$ | $29.5^{10}$ | $9^P$ |
| | | | 20 | 5 | .05 | 260 | 47 | 30 | $37.8^r$ | $30.0^{10}$ | $143^P$ |
| | | | 20 | 5 | .05 | 46 | 0 | 30 | $37.7^r$ | $29.5^{10}$ | $9^P$ |
| | | | 20 | 5 | .05 | 431 | 85 | 30 | $38.3^r$ | $31.8^{10}$ | $281^P$ |
| | | | 20 | 5 | .05 | 46 | 0 | 30 | $38.0^r$ | $30.1^{10}$ | $9^P$ |
| Kolka 1984[4] | | | | | | | | | | | |
| 3f | 58.7 | 1.6 | 50 | 16 | .15 | 395 | 68 | 9.2 | $37.8^e$ | $37.3^8$ | $731^T$ |
| 31 | 58.7 | 1.6 | 50 | 16 | .15 | 397 | 68 | 8.0 | $38.0^e$ | $37.8^8$ | $727^T$ |
| 3f | 58.7 | 1.6 | 50 | 19 | .15 | 39 | 0 | 170 | $37.7^e$ | $37.4^8$ | $231^T$ |
| 31 | 58.7 | 1.6 | 50 | 19 | .15 | 43 | 0 | 164 | $37.8^e$ | $37.8^8$ | $215^T$ |
| 3f | 58.7 | 1.6 | 35 | 9 | .15 | 41 | 0 | 20 | $36.8^e$ | $35.8^8$ | $133^T$ |
| | | | 35 | 9 | .15 | 320 | 47 | 75 | $37.6^e$ | $35.1^8$ | $487^T$ |
| 31 | 58.7 | 1.6 | 35 | 9 | .15 | 40 | 0 | 20 | $37.0^e$ | $36.0^8$ | $47^T$ |
| | | | 35 | 9 | .15 | 309 | 47 | 75 | $37.7^e$ | $34.5^8$ | $524^T$ |
| 3f | 58.7 | 1.6 | 35 | 9 | .15 | 43 | 0 | 20 | $36.9^e$ | $35.9^8$ | $132^T$ |
| | | | 35 | 9 | .15 | 405 | 64 | 35 | $37.9^e$ | $35.0^8$ | $866^T$ |
| 31 | 58.7 | 1.6 | 35 | 9 | .15 | 42 | 0 | 20 | $37.2^e$ | $36.3^8$ | $87^T$ |
| | | | 35 | 9 | .15 | 440 | 64 | 35 | $38.3^e$ | $35.2^8$ | $964^T$ |
| Saltin 1970 | | | | | | | | | | | |
| 1m | 84.0 | 2.1 | 10 | 4 | .05 | 175 | 23 | 30 | $37.0^e$ | $26.0^{10}$ | $27^P$ |
| 1m | 84.0 | 2.1 | 10 | 4 | .05 | 300 | 59 | 30 | $37.5^e$ | $27.0^{10}$ | $28^P$ |
| 1m | 84.0 | 2.1 | 10 | 4 | .05 | 475 | 94 | 30 | $38.0^e$ | $29.0^{10}$ | $140^P$ |
| 1m | 84.0 | 2.1 | 20 | 7 | .05 | 175 | 23 | 30 | $37.3^e$ | $29.5^{10}$ | $30^P$ |
| 1m | 84.0 | 2.1 | 20 | 7 | .05 | 300 | 59 | 30 | $37.3^e$ | $30.0^{10}$ | $150^P$ |
| 1m | 84.0 | 2.1 | 20 | 7 | .05 | 475 | 94 | 30 | $38.3^e$ | $32.0^{10}$ | $285^P$ |
| 1m | 84.0 | 2.1 | 30 | 13 | .05 | 175 | 24 | 30 | $37.1^e$ | $33.2^{10}$ | $130^P$ |
| 1m | 84.0 | 2.1 | 30 | 13 | .05 | 300 | 59 | 30 | $37.5^e$ | $34.0^{10}$ | $175^P$ |
| 1m | 84.0 | 2.1 | 30 | 13 | .05 | 475 | 94 | 30 | $38.8^e$ | $33.8^{10}$ | $280^P$ |
| Wagner and Horvath 1985 | | | | | | | | | | | |
| 10m | 70.8 | 1.9 | 28 | 11 | .05 | 52 | 0 | 120 | $36.7^r$ | $34.3^6$ | $36^N$ |
| 10m | 70.8 | 1.9 | 20 | 7 | .05 | 52 | 0 | 120 | $36.6^r$ | $31.2^6$ | $31^N$ |
| 10m | 70.8 | 1.9 | 15 | 5 | .05 | 52 | 0 | 120 | $36.6^r$ | $28.8^6$ | $30^N$ |
| 10m | 70.8 | 1.9 | 10 | 4 | .05 | 52 | 0 | 120 | $36.6^r$ | $27.2^6$ | $29^N$ |
| 10f | 59.3 | 1.7 | 28 | 11 | .05 | 51 | 0 | 120 | $36.8^r$ | $33.0^6$ | $32^N$ |
| 10f | 59.3 | 1.7 | 20 | 7 | .05 | 51 | 0 | 120 | $36.7^r$ | $28.8^6$ | $28^N$ |
| 10f | 59.3 | 1.7 | 15 | 5 | .05 | 51 | 0 | 120 | $36.6^r$ | $27.0^6$ | $27^N$ |
| 10f | 59.3 | 1.7 | 10 | 4 | .05 | 51 | 0 | 120 | $36.4^r$ | $25.0^6$ | $25^N$ |

KEY

- e Esophageal temperature
- r Rectal temperature
- 6 6 site mean Tsk calculation
- 8 8 site " " "
- 10 10 site " "
- p Potter balance
- t Total body weight loss, distributed in time according to local sweating rates.
- n No active regulatory sweating

[4] Kolka, M.A. 1984. Unpublished study titled "Local sweating modulations during the human menstrual cycle." USARIEM, Natick MA.

TABLE 1
Results of Paired Comparisons (predicted - observed)

| variable | mean error | confidence interval | t | sig. level | df |
|---|---|---|---|---|---|
| w | -.159 | [-.203, -.116] | -7.348 | .0000 | 84 |
| Tcr | -.307 | [-.393, -.222] | -7.149 | .0000 | 84 |
| Tsk | .475 | [ .234, .716] | 3.918 | .0001 | 84 |
| PMV | 1.292 | [ .453, 2.131] | 3.062 | .0029 | 84 |

TABLE 2
Table of Adjusted Means

| | n | ERR w | ERR Tsk | ERR Tcr | ERR PMV |
|---|---|---|---|---|---|
| Exercise Int: | | | | | |
| rest | 28 | -.1229 | -.0593 | -.3963 | .1855 |
| low | 29 | -.1019 | .4342 | -.2234 | .6949 |
| mod | 19 | -.1702 | 1.1200 | -.2209 | 2.3785 |
| high | 9 | -.4351 | .9090 | -.4821 | 4.3646 |
| overall F prob. | | .0000 | .0023 | .1149 | .0008 |
| critical diff. | | .1245 | .9374 | .3265 | 2.4839 |
| Gender: | | | | | |
| m | 57 | -.0980 | .5841 | -.4248 | 1.2264 |
| ff | 21 | -.2302 | .4352 | -.0439 | 1.1402 |
| fl | 7 | -.4472 | -.2915 | -.1394 | 2.2817 |
| overall F prob. | | .0000 | .1261 | .0003 | .6223 |
| critical diff. | | .1286 | .9097 | .3161 | 2.3999 |

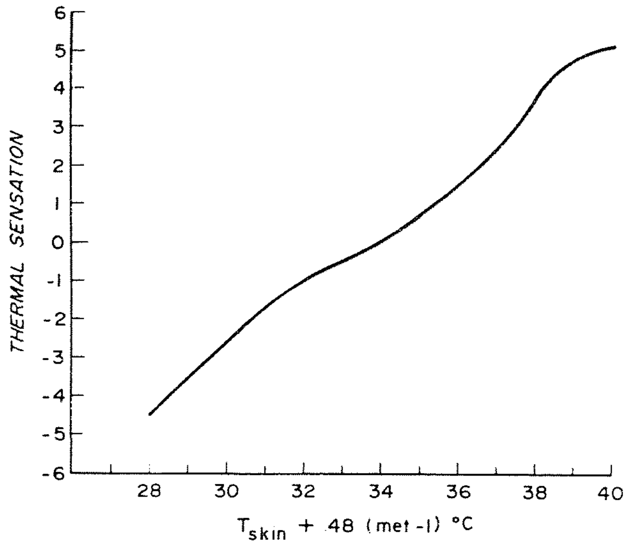


Figure 1 Thermal sensation prediction curve used by Pierce model for higher activity levels and transients (Berglund 1978).

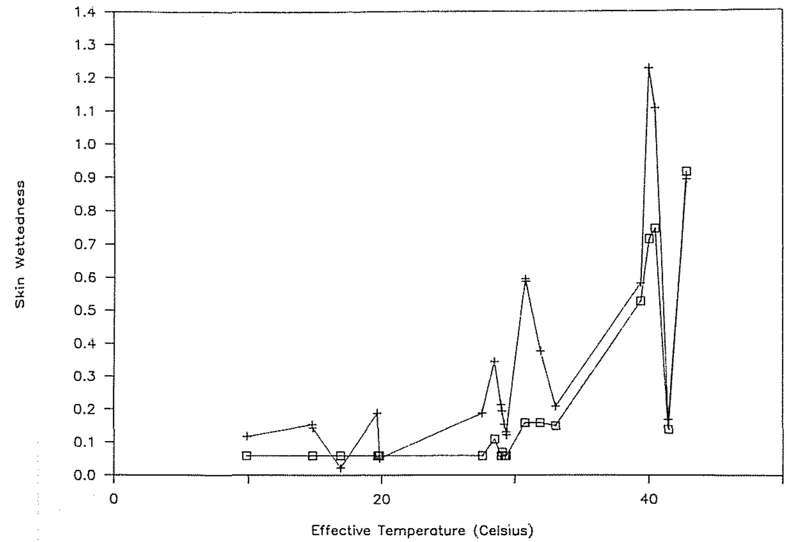


Figure 2 Observed (+) and predicted (□) values of skin wettedness for resting exposure.



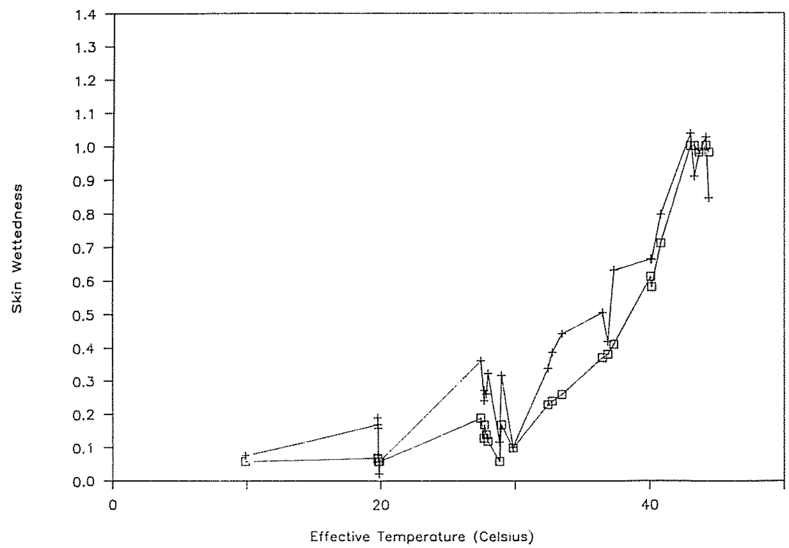


Figure 3 Observed (+) and predicted (□) values of skin wettedness for low exercise intensity.

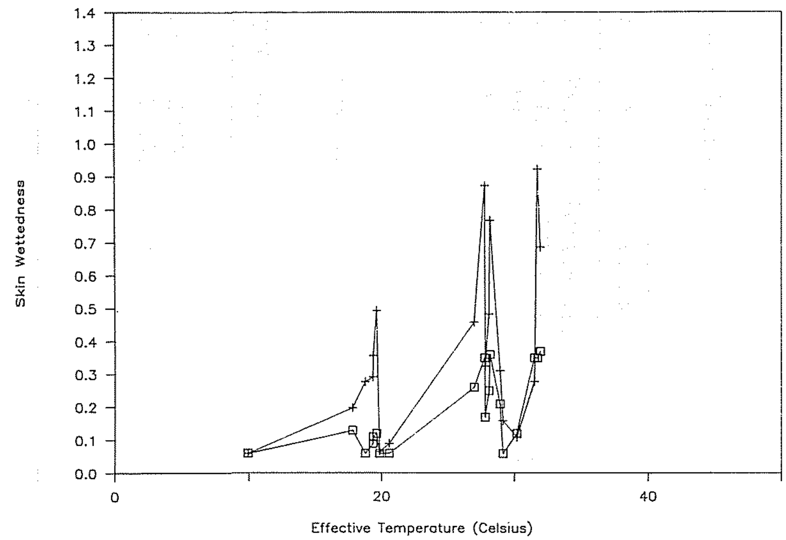


Figure 4 Observed (+) and predicted (□) values of skin wettedness for moderate exercise intensity.

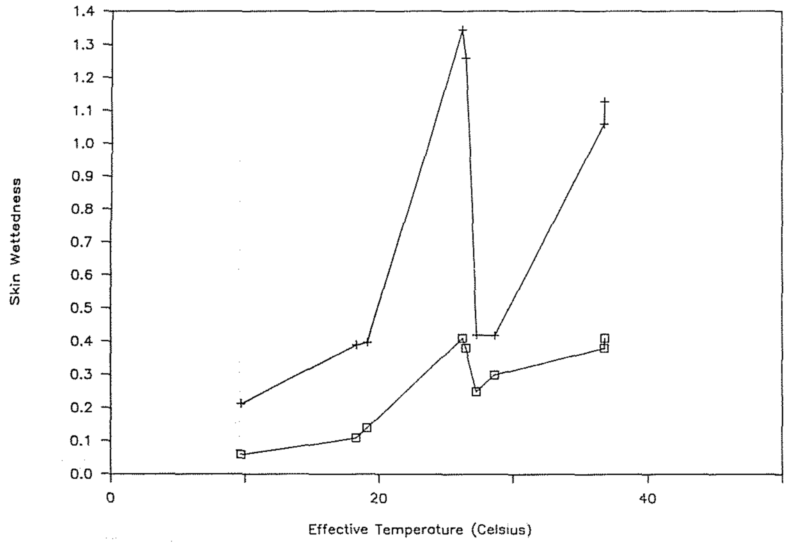


**Figure 5** Observed (+) and predicted (□) values of skin wettedness for high exercise intensity.

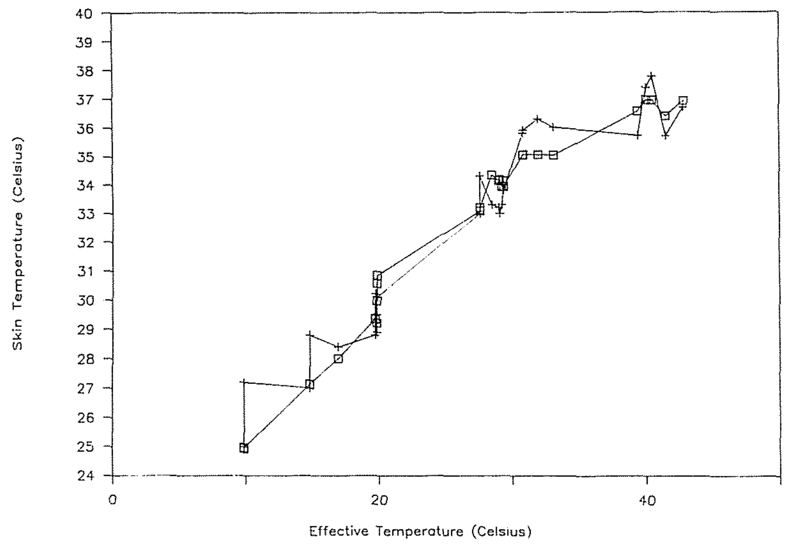


**Figure 6** Observed (+) and predicted (□) values of skin temperature for resting exposure.

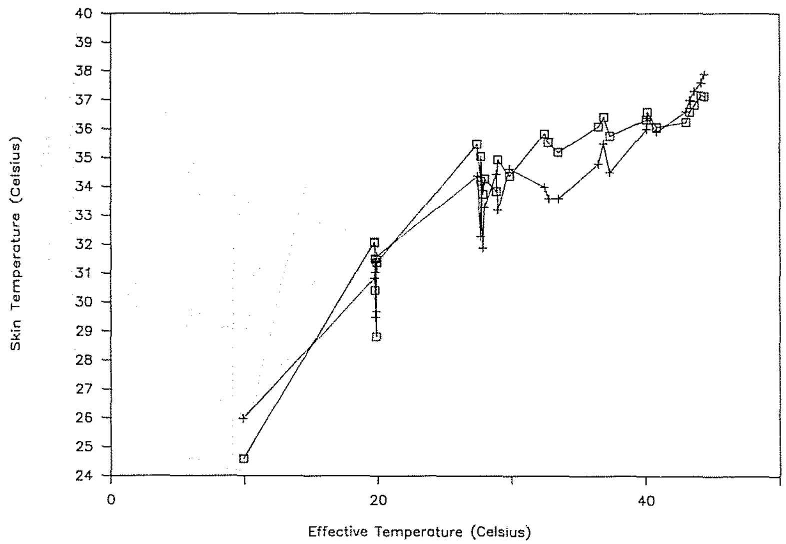


**Figure 7** Observed (+) and predicted (□) values of skin temperature for low exercise intensity.

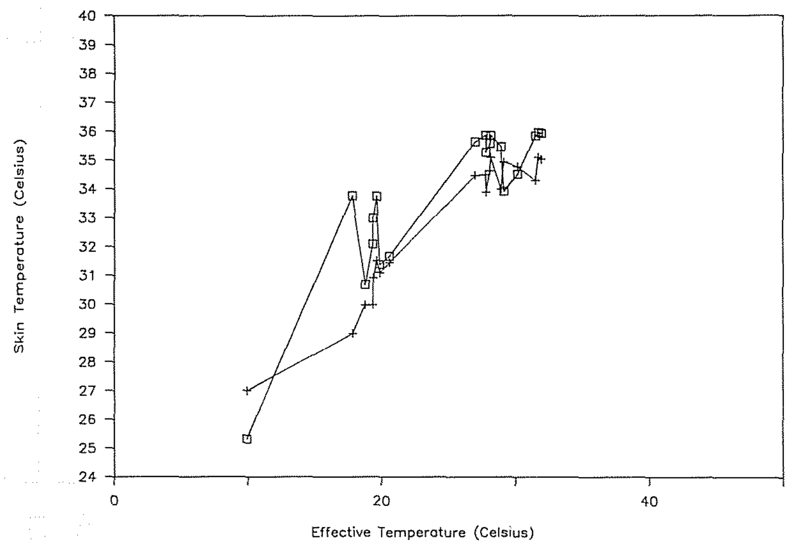


**Figure 8** Observed (+) and predicted (□) values of skin temperature for moderate exercise intensity.

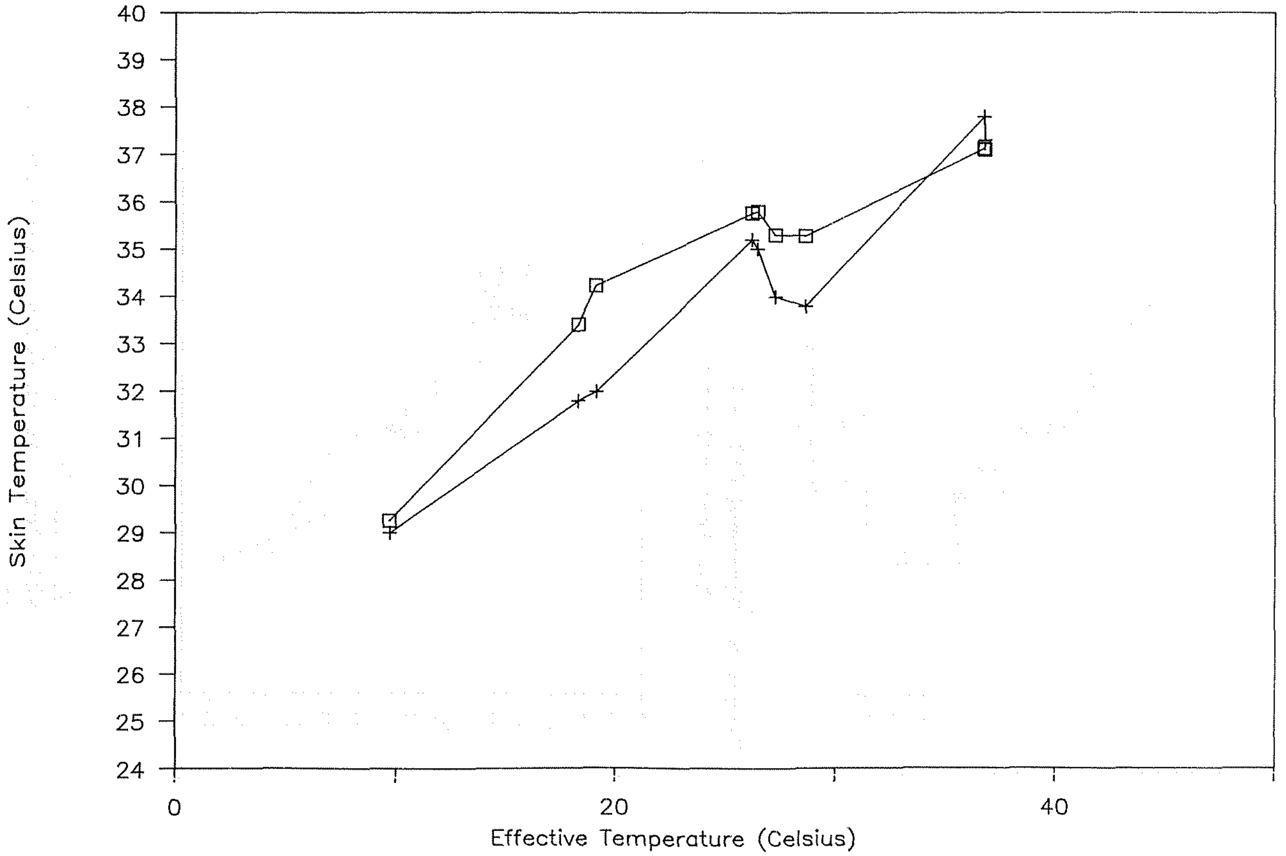


**Figure 9** Observed (+) and predicted (▭) values of skin temperature for high exercise intensity.

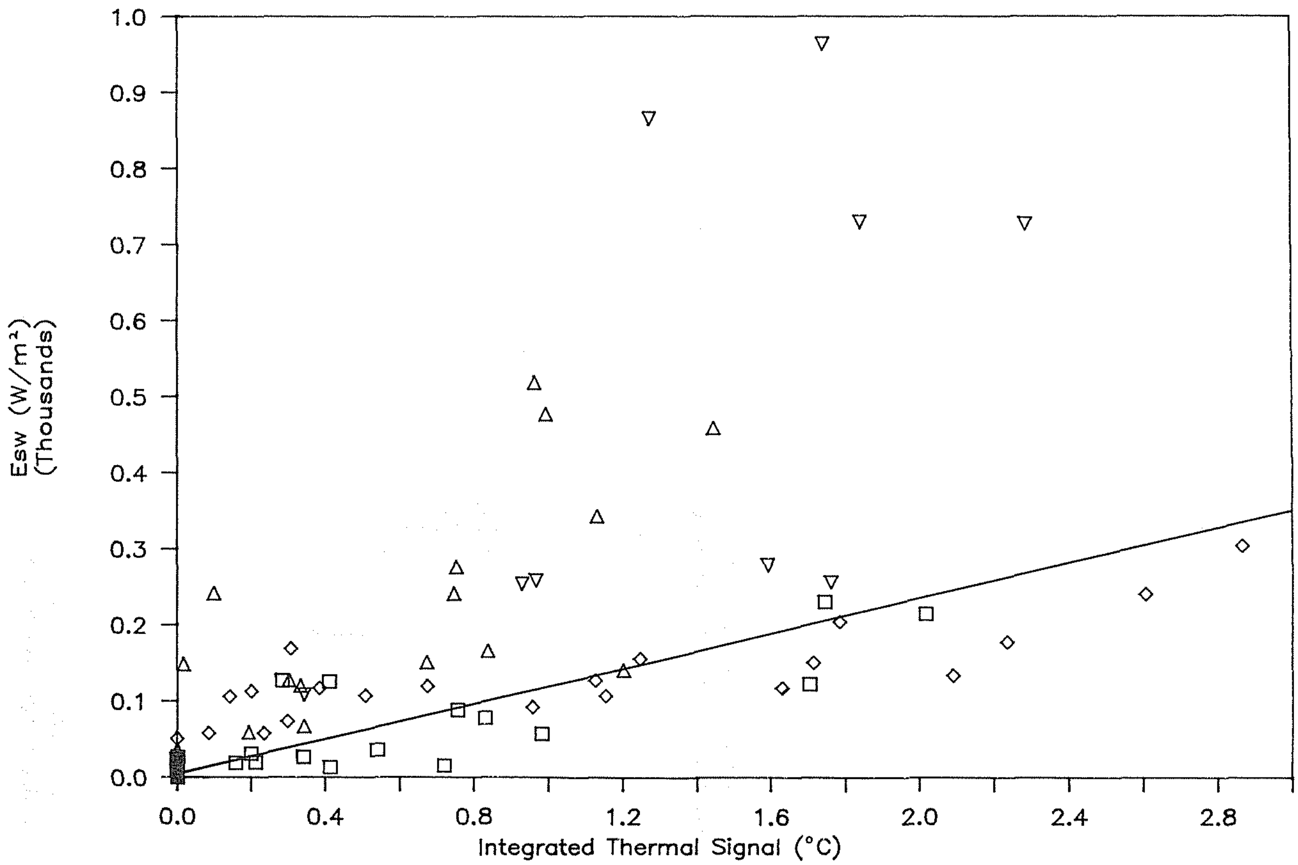


**Figure 10** Observed values of Esw versus the thermal effector signal for sweating at rest (▭), and at high (▽), moderate (◇), and low (△) exercise intensity. Solid line corresponds to Pierce model prediction for observed values of $T_{cr}$ and $T_{sk}$ [gain = $(170\ g \cdot m^{-2} \cdot hr^{-1})x(.68\ W \cdot hr \cdot g^{-1})$].

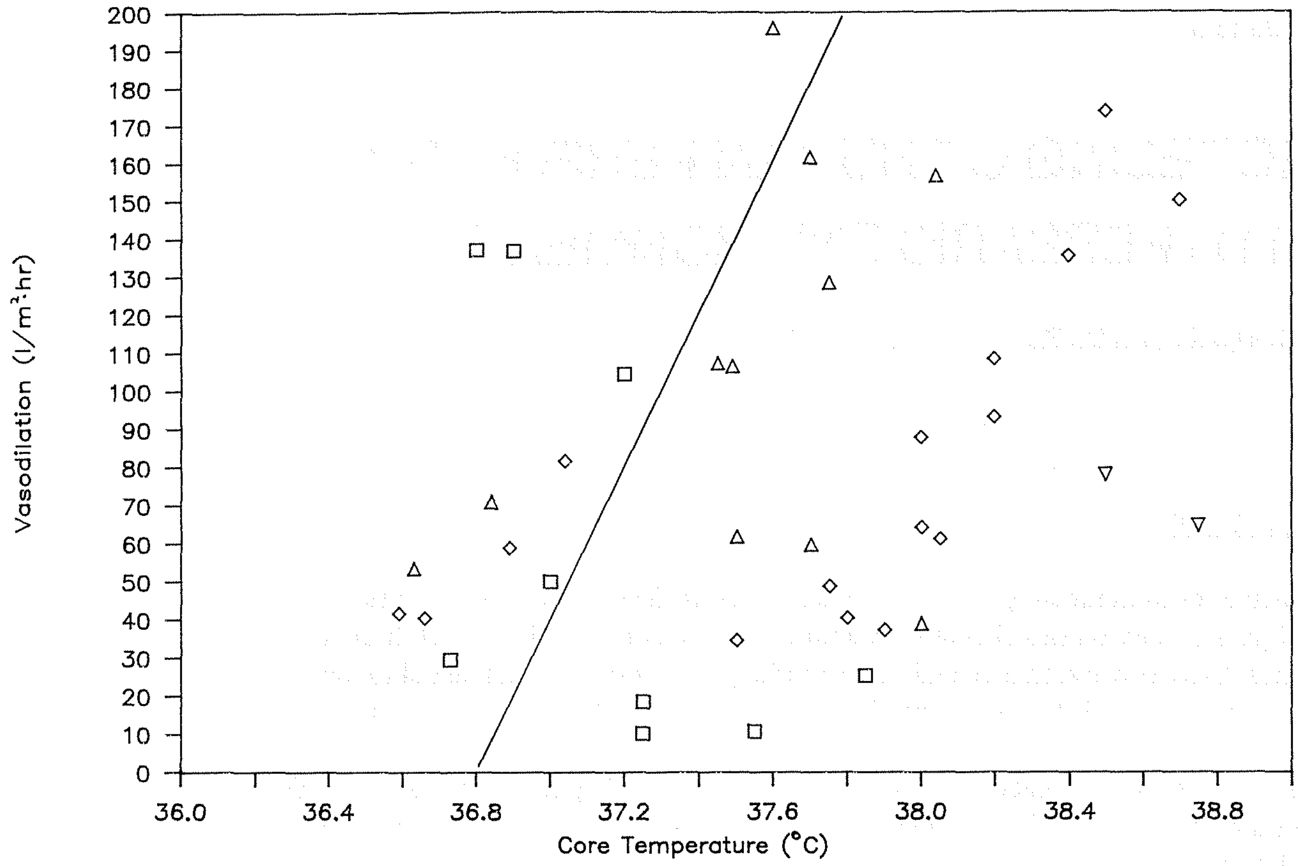


**Figure 11** Observed values of SKBF due to active vasodilation at rest (▭), and at high (▽), moderate (△), and low (◇) exercise intensity. Solid line corresponds to Pierce model prediction for observed values of $T_{cr}$ (gain = 200 $l \cdot m^{-2} \cdot hr^{-1} \cdot {}^{\circ}C^{-1}$).

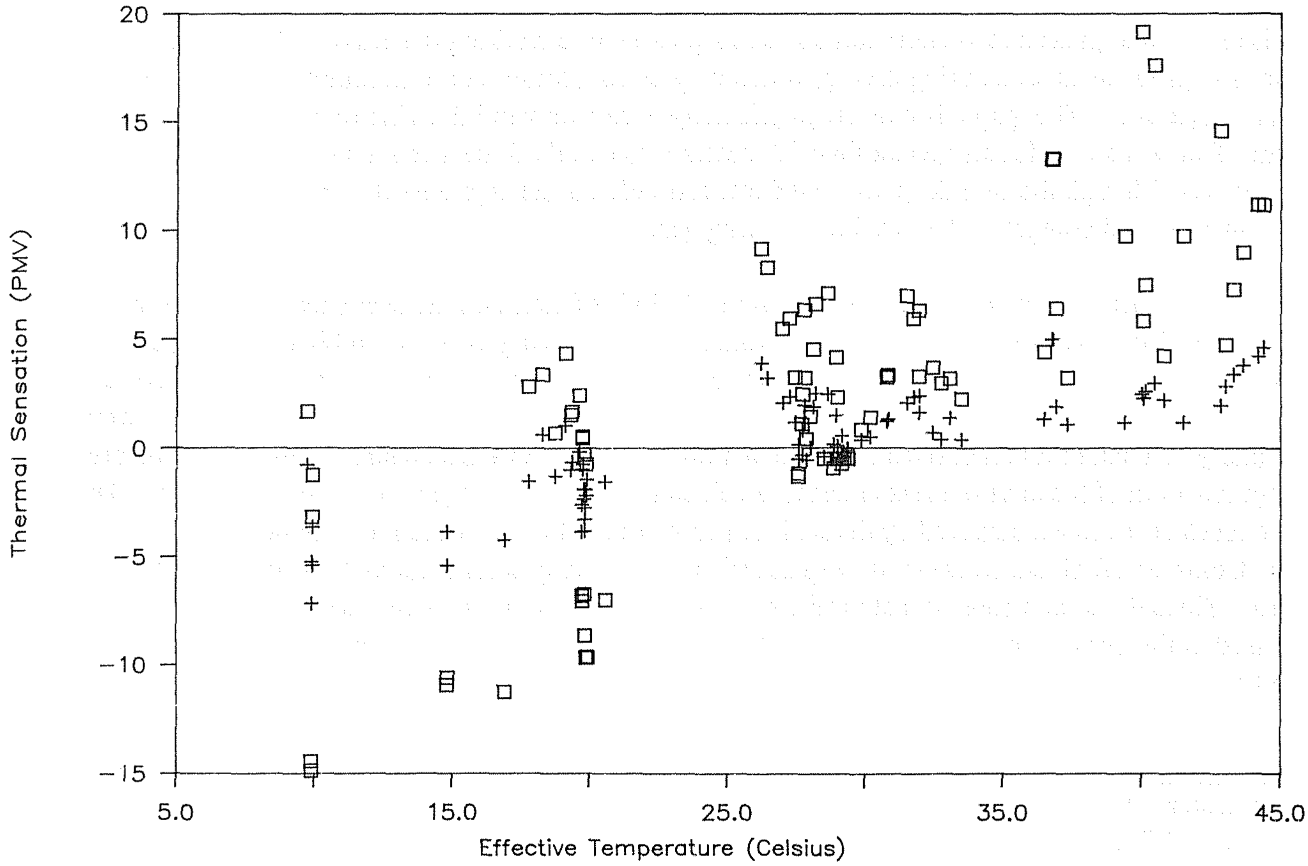


**Figure 12** Tsens (+) and PMV (▭) versus effective temperature.