## Title

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# THERMAL COMFORT UNDER AN EXTENDED RANGE OF ENVIRONMENTAL CONDITIONS

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## ABSTRACT

This paper describes the development of a chart in which lines of equal comfort are plotted across a wide range of environmental conditions. The chart can be used in the design of outdoor spaces and buildings where air velocity and radiant fields are outside their normal indoor ranges. The basis of the chart is the comfort index DISC, as predicted by the J.B. Pierce Foundation Laboratory two-node thermophysiological model. DISC is a function of skin temperature in cold conditions and of skin wettedness alone in hot conditions. It shows a greater sensitivity to humidity in hot conditions than does ET*. Examples of the chart are given for two clothing levels.

## INTRODUCTION

In the 1950s, Victor Olgyay collaborated with C. P. Yaglou to produce a "bioclimatic chart" (Olgyay and Olgyay 1953) plotting contours of equal comfort over an extended range of environmental conditions. The chart was the basis of a climatic design method described in Olgyay's book Design with Climate (1963) that had a great influence on architects. In this method, the designer superposes local climate data on the bioclimatic chart to determine the climatic modifications needed to assume occupant comfort. The modifications include solar control, air movement, and evaporative cooling for overheated periods, and solar gain for underheated periods.

A design procedure based on superimposed outdoor climate and occupant comfort requirements requires a close coupling between the outdoors and the location of the occupants. This close coupling exists of course in outdoor spaces, and in "envelope-dominated" buildings, where climate elements are available indoors in the form of sunshine through windows, natural ventilation, and thermal transfer through walls and roof. Most passively heated and cooled buildings fit into this category. Givoni and Milne have recently developed a variant of the chart, the "building bioclimatic chart" (Givoni 1976; Watson and Labs 1983) which incorporates on the chart the ranges of climatic modification that one might expect for various passive design features.

We felt it would be useful to redo the chart based on current ASHRAE comfort criteria, and using a rationally-derived index for determining comfort over the wide range of environmental conditions.

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## DESCRIPTION OF THE CHART

The chart (examples shown in Figures 1 and 2) plots the still-air human thermal comfort zone on a psychrometric chart. The air temperature is assumed to be equal to mean radiant temperature in the comfort zone. Outside the comfort zone, the chart has contour lines along which selected levels of added radiation or air velocity will restore the body to the nearest boundary of the comfort zone. The radiation values offset temperatures that are too low, and the air velocities offset temperatures that are too high. Combinations of radiation and air movement are not plotted in order to keep the chart readable. The levels of radiation and air movement represented on the chart extend to high values that are normally only encountered outdoors, and as a consequence the range of temperatures considered is wide. Three measures of radiation are given: mean radiant temperature, effective radiant field, and total horizontal insolation.

## THERMAL MODEL USED TO GENERATE CHART VALUES

The new values were obtained by simulating an assumed building occupant on the John B. Pierce two-node mathematical model of the human thermoregulatory system developed originally by Gagge et al. (1970). The model was used to find the loci of environmental conditions that produce equal levels of comfort or discomfort without having to resort to extensive experimental testing. The model is a simplification of more complex and specialized thermoregulatory models developed by Stolwijk and Hardy (1966) and has been found effective at predicting physiological response near the comfort zone under conditions of low to moderate activity.

The model considers man as two concentric thermal compartments representing the skin and core of the body. The skin compartment simulates the epidermis and dermis, with a thickness of approximately 1.6 mm and weighing about 10% of the total body weight. The temperature within each compartment is assumed to be uniform, so that the only temperature gradients are between compartments.

This latter assumption may limit the effectiveness of the model at predicting the effect of some asymmetrical environmental conditions caused by wind and radiation, but the extent of this cannot be determined at present. Similarly, since the model does not differentiate body surfaces into clothed and exposed skin portions but uses an average clothing resistance value for the whole surface, it may incorrectly estimate convective heat loss at high wind velocities and radiant gain under conditions of strong radiation. This follows because the exposed surfaces are disproportionately affected by changes in airfilm resistance or energy input at the surface. The extent of these effects is unknown. For the purposes of this project, one might assume that, since the contours on the bioclimatic chart represent comfortable conditions, strong thermal gradients will not be occurring across the skin surface or along body extremities and that the model will therefore simulate reality.

The model is described in detail in two reports (Gagge et al. 1976; Berglund and Stolwijk 1978), although some further development has taken place since these reports. The significant point to note here is that the measure for comfort/discomfort used in preparing the chart is based on skin temperature alone in cold conditions, and on skin wettedness (fraction of the skin covered by water) alone in hot conditions. This measure, termed DISC in the FORTRAN version of the model, was developed by Gagge from experimental findings that discomfort (as opposed to thermal sensation) is more closely linked to skin wettedness in hot conditions than to skin temperature.

## ASSUMED CONDITIONS UNDERLYING THE CHART

Clothing. The chart is intended to be as general as possible, for indoor and outdoor use. A clothing level of 0.8 clo (intrinsic) was chosen to represent typical clothing for both males and females in the cool part of the year. It also represents a compromise between indoor and outdoor clothing. A second chart uses 0.4 clo for warmer conditions. The most useful chart may reflect both clothing levels, with the higher clo level at temperatures below the comfort zone, and the lower levels at temperatures above. This will enlarge the effective comfort zone and reflect likely seasonal changes in clothing. In locations with large daily temperature swings, the 0.8 clo chart provided here may be the most useful, because clothing changes are not commonly made within the day.

Activity Level. An activity level of 1.3 met (75.4 $Wm^{-2}$) was chosen as representing typical levels of activity in home, outdoor, and even office environments. This level corresponds to light household work, to slow walking as is common in shopping indoors and outdoors, and to office work where the occupant is required to get up and move around occasionally.

Comfort zone boundaries. The criteria for the comfort boundaries are taken from ASHRAE Standard 55-81 (1981) in the following way: the clothing and activity levels specified in the standard (0.5 clo in summer and 0.9 clo in winter; 1.2 met) were simulated on the J.B. Pierce model for the high and low boundary temperatures of the standard's summer and winter comfort zones at 50% relative humidity. Between these boundaries, the standard states that 80% or more of the occupants find the environment thermally acceptable.

The average of the summer and winter values of DISC computed for these temperatures were used as the criteria for setting the upper and lower temperature boundaries of the bioclimatic chart comfort zone. For each set of wind, radiation, and humidity conditions, the model was used to iteratively solve for the temperature at which DISC had the comfort boundary value. The set of climatic conditions could then be plotted on the temperature and humidity axes.

In hot conditions, the DISC contours were found to slant more to the left than the contours of ET* that define the ASHRAE comfort zone, meaning that this measure is more sensitive to humidity than ET*. This seems reasonable since ET* assigns a weight to skin temperature as well as skin wettedness. To the extent that skin temperature depends on air temperature, this weight should cause ET* to be less sensitive to humidity, and more closely tied to air temperature. Since the DISC values used for plotting contours on the chart are based on ASHRAE comfort zone boundaries at 50% relative humidity, the contours of DISC will allow higher air temperatures than the hot boundary of the ASHRAE comfort zone at lower relative humidity values, and lower temperatures above. At 25% relative humidity this chart allows approximately $1^{\circ}C$ higher temperature than the ASHRAE comfort zone.

Although there are no upper and lower limits to humidity from a thermal comfort standpoint, limits are suggested for the still air comfort zone based on the following practical considerations: vapor pressures above 1.86 kPa (14 mm Hg) will cause moisture and mold problems indoors, and vapor pressures below 0.67 kPa (5 mm Hg) are likely to cause respiratory discomfort. The higher limit would probably not apply to outdoor conditions.

Wind. Wind below 0.15 $ms^{-1}$ has the same thermal effect as still air in the model. The chart uses 0.26 $ms^{-1}$ as a minimum because of the body-motion-induced wind at the assumed 1.3 met activity level. McIntyre (1978) found that wind indoors from overhead fans was not acceptable above 2 $ms^{-1}$ due to the annoyance caused by the wind and fan noise. The bioclimatic chart, however, applies also to outdoor conditions, where acceptable limits are higher. Hunt et al. (1976) and subsequent researchers have found the maximum mean velocity in low turbulence conditions to be 6 $ms^{-1}$, above which mechanical effects of wind pressure on the occupant and his/her clothing produce discomfort. As the turbulence levels increases, the acceptable mean velocity decreases. In practice, these limits are not reached on the chart because the incremental thermal benefit of wind becomes negligibly small above 4 $ms^{-1}$.

Radiation. Several radiation values are plotted on the chart. First, the effective radiant field (ERF) is a convenient measure of the net radiant heat flux to or from the human body. It is commonly used to describe the additional long-wave radiation energy received by the body when surrounding surface temperatures are different from the air temperature. Second, the surrounding surface temperature may be expressed as mean radiant temperature (MRT), as defined in Fanger (1972). The ERF on the human body is related to MRT by:

$$\mathrm{ERF} = f_{eff} * h_r\ (\mathrm{MRT} - T_a)$$

where

$f_{eff}$ is the fraction of the body surface exposed to radiation from the environment,
$h_r$ is the radiative film coefficient, and
$T_a$ is the air temperature.

Third, for solar radiation, the most extensively published measure is the total (direct plus diffuse) radiation falling on a horizontal surface ($I_{TH}$). The value of $I_{TH}$ varies with solar elevation. In addition, the area of the human body exposed to solar radiation, and therefore the solar energy received by the body, also varies with solar elevation. In order to keep the chart simple, the total radiation $I_{TH}$ must be plotted for a specific solar elevation. The elevation of 45 degrees was chosen as an average value for the contiguous United States. Correction factors for other elevations are provided in Figure 3. The equivalence between ERF, MRT, and $I_{TH}$ involves the following assumptions:

1. The influences of radiation and convection are assumed to be equal in plotting MRT.
2. Long-wave radiation as represented by MRT and ERF is treated as uniformly distributed. There is no provision for the directional characteristics of the body's exposed surfaces interacting with non-uniformities in the long-wave radiant field.
3. The DuBois area of the assumed person ($A_D$) = 1.8 $m^2$.
4. The projected area of standard man exposed to direct beam sunlight ($A_p$), where solar elevation $\beta = 45^o$:

   $A_p / A_D = 0.23$ (Fanger 1972)
   $A_p = 0.41\ m^2$.

5. Area of standard man exposed to diffuse, reflected, and long-wave radiation:

   $f_{eff} = 0.72$ (Fanger 1972)
   $0.72 * 1.8 = 1.28\ m^2$ over body.

6. Diffuse-sky and ground-reflected solar radiation are each assumed to be uniformly distributed on one-half the exposed portion of the body:

   $0.72 * 0.9 = 0.64\ m^2$ over half body.

Because the measure effective radiant field (ERF) incorporates the $f_{eff}$ of the receiving subject, the following equality can be written for absorbed energy from long-wave and short-wave sources:

$$ERF * \alpha_{LW} = [0.72 * (0.9/1.8) * (I_d + I_r) + (0.41/1.8) * I_N] * \alpha_{SW} \qquad [1]$$

<u>where</u>

$\alpha_{LW}$ is long-wave absorptivity, $\simeq 0.95$
$\alpha_{SW}$ is short-wave absorptivity, $\simeq 0.67$ for (white) skin and average clothing
$I_N$ is direct beam solar radiation measured perpendicular to the beam, $Wm^{-2}$
$I_d$ is diffuse irradiance, $Wm^{-2}$ of an upward-facing horizontal surface
$I_r$ is reflected irradiance, $Wm^{-2}$ of a downward-facing horizontal surface.

Because $I_N = (I_{TH} - I_d)/\sin\beta$, where $I_{TH}$ is total solar irradiance of a horizontal surface, Equation 1 can be rewritten:

$$ERF * 0.95 = [(0.72/2) * (I_d + I_r) + (0.41/1.8 * \sin\beta)(I_{TH} - I_d)] * 0.67 \qquad [2]$$

$I_r$ is assumed to be $0.20 * I_{TH}$: this is an average value for both vegetated and built-up areas given by Geiger (1965).

Clear day values for $I_{TH}$ and $I_d$ are obtained from Monteith (1973) for 45° solar elevation:

$I_{TH} = 665\ Wm^{-2}$
$I_d = 165\ Wm^{-2}$

At 45° solar elevation, $\sin\beta = 0.71$.

Substituting in Equation 2, ERF = 190 $Wm^{-2}$, i.e. under the conditions assumed, ERF is thermally equivalent to $0.29 * I_{TH}$, or $I_{TH} = 3.5 * ERF$.

This ratio is used in plotting the ERF and $I_{TH}$ values on the chart.

<u>Relation to Directional Radiant Temperature.</u> McIntyre (1975) summarized results from several experiments showing that sedentary subjects would be uncomfortable in conditions in which the difference in the plane radiant temperatures from one side to the other exceeded 20°C. This difference is variously called directional radiant temperature (DRT), vector radiant temperature ($T_V$), and radiant field asymmetry, and may be described as the difference in radiant temperatures of two hemispheres facing opposite sides of a receiving plane. McIntyre's suggested maximum DRT is similar to or higher than that found by other researchers (ASHRAE Thermal Standard 55-81, for example, specifies 10°C), and might therefore be regarded as the upper limit to acceptable DRT. Since solar radiation is strongly directional, it is interesting to see at what level of solar gain, expressed as $I_{TH}$, this indoor comfort limit is reached.

Working from the definition of DRT, one may assume a vertical plane illuminated by direct sun $I_N$ on one side, and by diffuse, reflected, and long-wave radiation equally on both sides. The energy absorbed from the direct sun can be set equal to the absorbed radiant flux resulting from a DRT of 20°C:

$$I_N * \cos\beta * \alpha_{SW} = DRT * h_r$$

where $h_r = 6\ Wm^{-2}\,{}^{o}C^{-1}$.

At a 45 ° angle of incidence (solar altitude),

$$I_N * 0.71 * 0.67 = 20^{o}C * 6\ Wm^{-2\,o}C^{-1}$$
$$I_N = 253\ Wm^{-2}$$

A vertical plane, of course, does not represent the human body very well. If one does this calculation using the two vertical halves of the human as a rough approximation of the two receiving planes of DRT, and making a more precise distribution of solar gain onto the sunlit half of the body by using $I_N * A_p$ , the resulting maximum acceptable value of $I_N$ comes out close to the above approximation, about ten percent higher.

Expressing this solar gain in terms of total radiation on the horizontal:

$I_{TH} = I_N * \sin\beta + I_d$. Assuming $I_d = 0.25\ I_{TH}$, then
$I_{TH} = 179 + 60 = 239\ Wm^{-2}$ corresponding to DRT = 20°C.

$239\ Wm^{-2}$ is a relatively low level of $I_{TH}$ for outdoor conditions, where values of $700\ Wm^{-2}$ and higher are common at midday in temperate climates. It is probable that indoor tests of stationary lightly clothed subjects represent only the most sedentary outdoor activities, and that typical outdoor subjects are more active, mobile, and exposed to wind. Each of these influences reduces the DRT experienced by the typical outdoor subject over time, and would allow higher levels of $I_{TH}$ to be judged acceptable.

## OTHER APPROACHES

The modeling approach used here differs from that underlying the ISO Thermal Comfort Standard 7730 (1984), and although comfort zone boundaries correspond closely for still air and when mean radiant temperature equals air temperature, the values predicted for the hot and cold extremes differ significantly. Explicating the differences is beyond the scope of this paper, but would be an interesting project for the future.

## CONCLUSION

The bioclimatic chart originally developed by Olgyay in the 1950s has been revised, using the J.B. Pierce two-node thermophysical model and the ASHRAE Thermal Standard 55-81, to determine the equal comfort levels under an extended range of environmental conditions. Such conditions occur in outdoor spaces and in envelope-dominated buildings where there is close coupling between the indoor and outdoor environments. The bioclimatic chart is presented here in psychrometric chart format. Although the still air comfort zone resembles the original one fairly closely, the wind and radiation lines are markedly different. It can also be seen that the skin wettedness measure used by DISC in hot conditions predicts a higher sensitivity to humidity than does ET*, resulting in a more slanted right-hand boundary to the comfort zone than that given by the ASHRAE standard.

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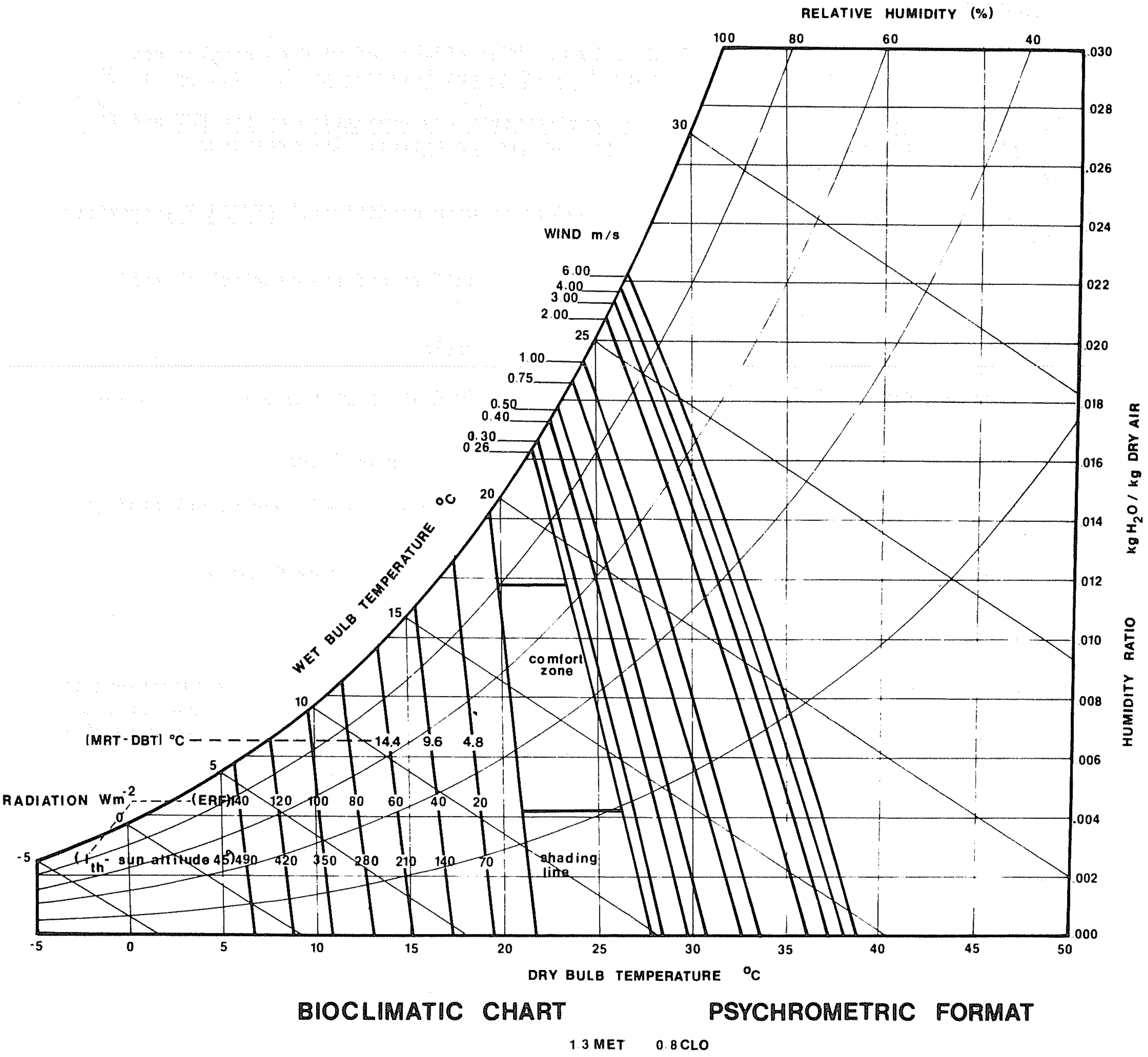

*Figure 1. Bioclimatic chart, 1.3 met, 0.8 Clo*

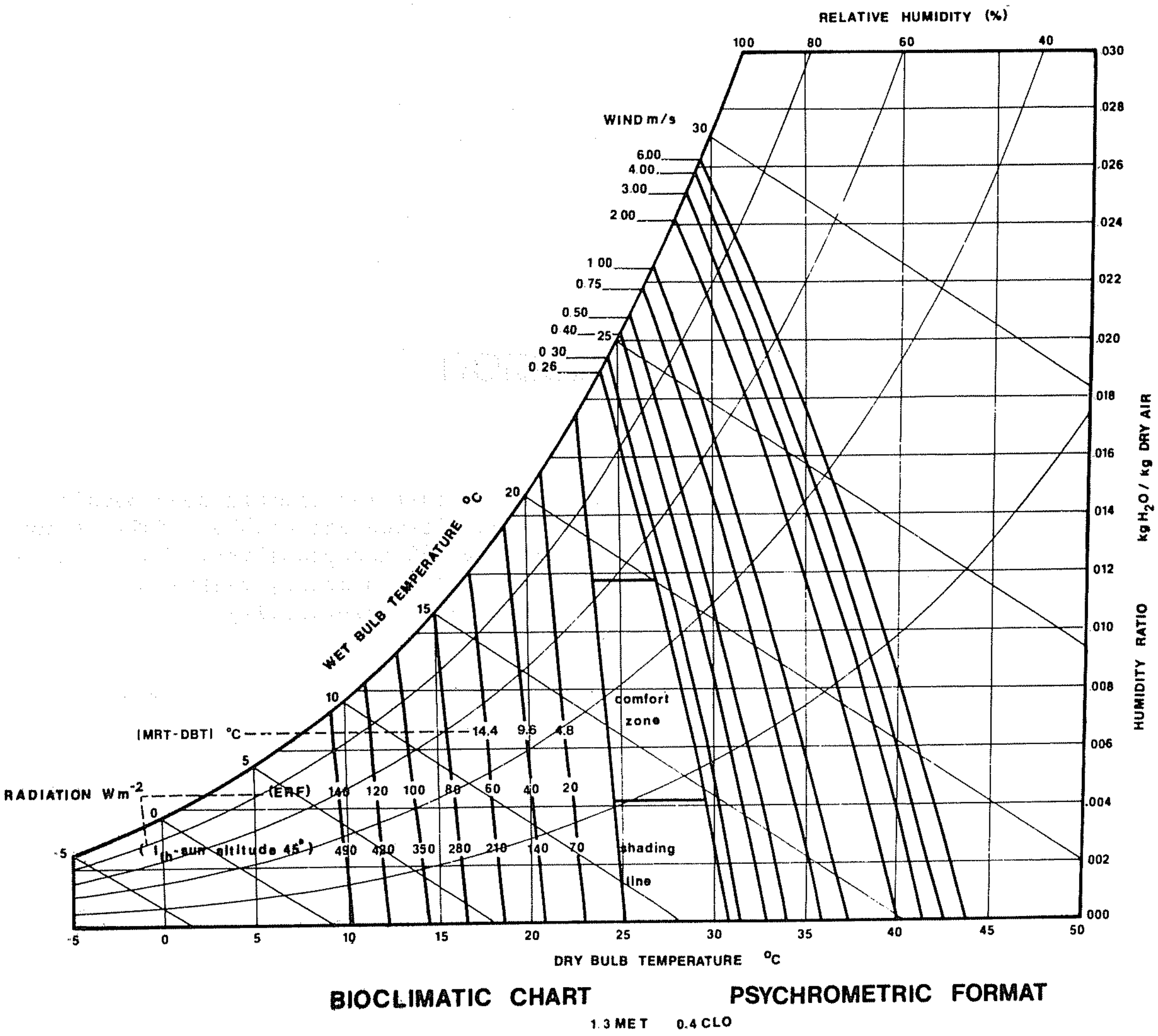

*Figure 2. Bioclimatic chart, 1.3 met, 0.4 Clo*

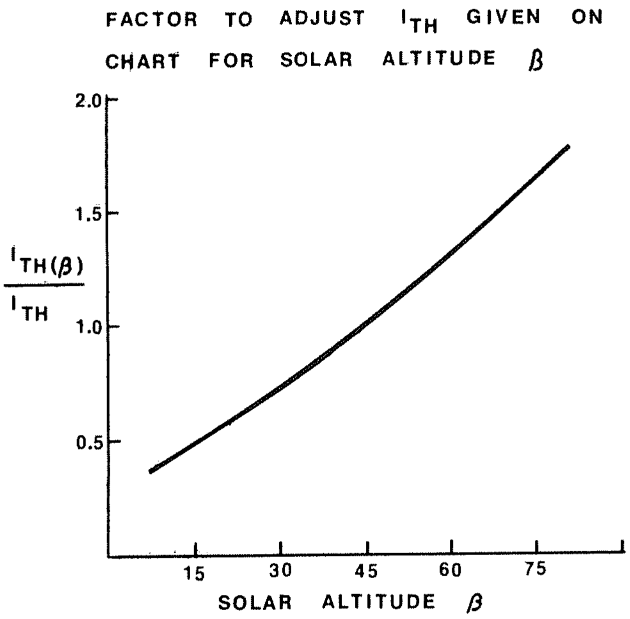

*Figure 3. Factor to adjust $I_{th}$ given on chart for solar altitude*

# Discussion

B.W. OLESEN, Bruel & Kjaer, Denmark: The authors state that the comfort zone boundaries in ASHRAE 55-81 will result in 80% or more finding the conditions acceptable. This is not correct. The comfort zone corresponds to approximately 90% acceptability. The additional 10% is due to problems with discomfort from local exposures to draft, radiant asymmetry. So the estimated limits in the present paper are based on 90% acceptability.

ARENS: The authors agree with Dr. Olesen's explanation of the assumptions underlying the ASHRAE 55-81 comfort zone.