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# THERMAL COMFORT DURING CYCLICAL TEMPERATURE FLUCTUATIONS

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## ABSTRACT

In order to determine the effect of cyclical temperature fluctuations on thermal comfort, 804 subjects were exposed to various basal temperatures (64, 67, 73, 79 and 85 FET*) which fluctuated at different amplitudes, A, (2, 4, 6, 8 and 10F) at rates of 2, 4, 6, and 8F/h. From their responses, equations were developed which enabled the prediction of the thermal sensation votes at the high and low points of the cycle both when the temperatures were increasing and decreasing from the basal condition. The results showed for humans engaged in near-sedentary activities while wearing light clothing, if the temperature conditions for comfort are met, the thermal environment will be acceptable if (a) the rate of change does not exceed 6F/h (3.3°C/h) and (b) the peak-to-peak amplitude is equal or less than 6F or ±3F (3.3°C or ±1.6°C). The conditions will be unacceptable both in and out of the comfort envelope at temperatures which (a) fluctuate at rates greater than 6F/h (3.3°C/h) or (b) have peak-to-peak amplitudes which are greater than 6F or ±3F (3.3°C or ±1.6°C). The equations were also used to predict the thermal sensations under ramp conditions. The most comfortable ascending ramp condition is when the basal temperature is increasing from between 70F and 74F at the rate of 1F/h. The most comfortable decreasing ramp conditions is when the basal temperature is falling from between 78F and 84F at the rate of 1F/h.


## INTRODUCTION

In comfort research, the critical independent variables associated with man are clothing and activity; those concerned with the thermal environment are the dry bulb temperature, water vapor pressure, mean radiant temperature, and the air velocity. Even though the thermal conditions to which man is exposed are never constant for long periods of time, time as a variable in comfort research has received only modest examination.

As Wyon (1) points out, manual operation of radiators, ventilation fans, thermostats, doors, windows and window-blinds, can give rise to large and unsystematic changes in indoor climate. Cyclic variations occur with automatic controls. In passing between buildings or between different areas in the same building, abrupt changes are experienced in the thermal environment. Temporal changes in individual activity alter the basal metabolic rate and the addition or removal of clothing can produce variations in heat balance, and both activity and clothing changes result in changes in the basic physiologic and affective responses of the individual concerned. In short, the steady-state temperature conditions that characterize most of the comfort research to date are, in

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practice, the exception rather than the rule.

In general, three types of non-steady-state conditons can be identified. The first involves discrete conditions such as those experienced when going from the home to the automobile to the supermarket and return. Study of this temporal dimension was the subject of recently reported research by the Kansas State University Institute for Environmental Research for the American Society of Heating, Refrigerating and Air Conditioning Engineers (21). It showed that when an individual entered a thermally-comfortable environment after spending an hour in either an uncomfortably cool condition [60F (15.6°C)] or an uncomfortably warm condition [90F (32.2°C)] the initial "shock" of entering the neutral condition [74F (23.3°C)] was short-lived and within 15 minutes, adaptation to the neutral condition occured.

The second type of temperature fluctuation is known as ramps or drifts and is characterized by the slow decrease in temperature that accompanies the night set-back of thermostats. The effect of these drifts has been studied in ASHRAE-support research at the John Pierce Foundation Laboratories. In one study, Berglund and Gonzales (3) showed that comfort could be achieved by 80% of the occupants when the basal temperature was 76.8F (24.9°C) and the occupants were wearing a clo ensemble of 0.5; at 75.5F (24.2°C) with a clo of 0.7; and at 74.3F (23.5°C) with a clo of 0.9 and the temperature was increasing or decreasing from the basal temperature by 3F (1.8°C) at the rate of 1F (0.6°C) per hour.

The third condition is related to cyclical temperature fluctuations. These fluctuations are attributable to such factors as thermostat tolerances, the size and effectiveness of the heating and cooling systems, and the thermal efficiency of the structure (storm windows, insulation and infiltration). This paper will describe the findings of a study designed to measure thermal comfort as a function of cyclical temperature fluctuations.

## BACKGROUND

In one of the early references to the temporal aspects of the thermal response Gagge, Stolwijk, and Hardy (4) demonstrated that going from a neutral condition to a cool condition produced greater discomfort than going from a neutral condition to a warm condition when the absolute temperature difference was the same. The temporal aspects of the thermal sensation were also identified in the comfort studies by Rohles and Nevins (5), who showed that a type of sensory adaptation to the thermal environment occurs which is similar to the dark adaptation experienced when entering a movie theatre. In that study during the first hour of exposure the college-age subjects engaged in a near-sedentary activity were significantly warmer than later in the exposure period and during this first hour the men were significantly warmer than women; in fact, only after an exposure of 1.5 h were the thermal sensation responses of the men and women similar.

In another study specifically designed to study the effects of fluctuating temperatures and relative humidity on the thermal sensations, college students who were engaged in near-sedentary activities were tested in 13 conditions in which the peak-to-peak amplitude of the temperature fluctuation ranged from 1F to 6F (0.6°C-3.3°C) and the rate of fluctuation ranged from 3.0F/h to 19.7F/h (1.8°C to 11.8°C). From this study by Sprague and McNall (6) it was concluded that "no serious occupancy complaints should occur due to temperature fluctuations when the following conditions are met:

$$\Delta T^2 \text{ (CPH)} < 15$$

where $\Delta T$ is the peak-to-peak amplitude of the temperature fluctuation and CPH is the cycling frequency in cycles per hour." As an example they suggest that if $\Delta T$ = 2F then CPH < 3.75 cycles would be an acceptable cycling rate; in constrast if the CHP was 7.5, then a $\Delta T \geq \sqrt{2} = 1.4$ would be an unacceptable periodic amplitude. The authors then state that the conclusion does not apply to controlled radiant systems where the mean radiant temperature fluctuates.

Wyon and his collegues at the Technical University of Denmark in Copenhagen (1) studied the effects of temperature swings of 0.15°C/min (16.2F/h) and

0.50°C/min (54F/h) with nude and clothed subjects while working and resting. They compared their findings with those of Sprague and McNall (6) whose limit "would permit ranges of only 1°C (1.8F) and 0.3°C (0.54F) for rates of 0.15°C/min (16.2F/h) and 0.50°C/min (54F/h) respectively." They indicated that "on more than half the occasions when subjects were exposed to temperature swings at 0.15°C/min (16.2F/h) the tolerated range was over 3.2°C (5.8F). ...(this rate) lies between the two greatest rates of change investigated by Sprague and McNall which were 0.18°C/min (19.7F/h) and 0.13°C/min (14F/h). Their assumption that the square of amplitude and rate of change should be a constant implies that the tolerated amplitude should be less for greater rates of change." They found the reverse to be true with clothed working subjects who tolerated swings greater than 9.2°C (16.6F) on more than half the exposures. In conclusion, their study demonstrated that wider swings can be tolerated when the rate of change is greater and second, subjects tolerated wider swings of air and skin temperatures when performing mental work than when resting.

A different approach to the study of man's sensitivity to temporal variations in the thermal environment was made by Griffiths and McIntyre (7). In their research, comfort responses were examined with sedentary subjects under three different rates of temperature change from a basal condition of 23°C (73.4F). From this temperature both increments and decrements of 2,4, and 6F/h (1.1, 2.2, and 3.3°C/h) occurred over a six hour period with a 30 minute break for lunch. From this research, they concluded that the useful boundary for temperature change about a basal temperature of 23°C (73.4F) would range from ±2.7°C to ±5.4°C (±4.9F to ±9.7F).

More recently Nevins, et al., (8) exposed 18 subjects, 7 males, ages 22-32, 5 males, ages 18-24 and 6 women, ages 33-60 to determine the preferred ambient temperature while exposed to cyclic variations in the dry bulb temperature at a constant 50% rh. The physical activity level was near-sedentary. The results showed that the preferred ambient temperature was approximately 78F (25.6°C) which agrees with the above noted study by Rohles and Nevins (5) and Fanger (9). However, their findings did not agree with Rohles and Nevins (5) who reported that males felt warmer than the females during the first hour of exposure and Wyon (1971) who reported that males "felt hotter and reacted more rapidly than women to changes in temperature." They also found that older subjects preferred a warmer environment than the younger subjects which is opposite to the findings of Rohles and Johnson (10). In the second part of their study they found that increases in humidity affect discomfort judgments more in men than in women, a finding which also agrees with Rohles and Nevins (5).

The findings of all of the research described must be considered in light of ASHRAE Standard 55-74 (11), which specifies the thermal environment conditions for human occupancy, and the Emergency Building Temperature Restriction Plan of 1979, which states that non-residential buildings are required to maintain summer conditions of 78F (25.6°C) dry bulb temperature/65F (18.3°C) dew point temperature for cooling and 65F (18.3°C) for heating. The ASHRAE Standard states that the Adjusted Dry Bulb Temperature which is the arithmetic average of the Dry Bulb Temperature and the Mean Radiant Temperature should be between 71.5F (21.9°C) and 77.6F (25.3°C) at 0.55 in. (14mm) Hg (water vapor pressure) and between 72.6F (22.6°C) and 69.7F (20.9°C) at 0.2 in. (5 mm) Hg. The Standard further specifies that if those conditions are met "the rate of change of dry bulb temperature or the mean radiant temperature in the occupied space shall not exceed 4F/h (2.2°C/hr) if the peak-to-peak swing in the dry bulb temperature or in the mean radiant temperature is 2F (1.1°C) or greater during each cycle." "The rate of change of the water vapor pressure shall not exceed 4.5 mm Hg/h if the peak-to-peak swing in water vapor pressure is 2.0 mm Hg or more during each cycle." This could be interpreted to mean that if the peak-to-peak amplitude does not exceed 4F (2.2°C) the rate of change is boundless.

When these research findings were considered in the light of the current energy shortage, it became obvious that additional research was needed to examine man's responses to cyclical temperature fluctuations. The response to drifts has been defined as well as the response to discrete temperature changes; the purpose of the present study was to examine the comfort responses during cyclical temperature fluctuations.

EXPERIMENTAL DESIGN

Four independent variables were selected for study: (1) $T_B$, the basal temperature about which the fluctuations would occur; (2) $r_1$ the initial rate of change in temperature in F/h; (3) $r_2$, the subsequent rate of change in temperature in F/h; and (4) A, the peak-to-peak amplitude of cyclic variation. Using a central composite rotable design described by Cochran and Cox (12) 31 test conditions were generated for study. Each test was repeated four times, twice when the initial fluctuation from a steady state condition was increasing and twice when the initial fluctuation from steady state was decreasing. These generated 124 tests (31 x 4 replications). In addition two steady state or non-fluctuating tests were conducted at each of the following 5 effective temperatures (rh = 50%): 64 FET* (17.8°CET*), 67 FET* (19.4°CET*), 73 FET* (26.1°CET*), and 85 FET* (29.4°CET); these increased the total number of tests by 10 (5 x 2) for a grand total of 134 tests. Six college students (3 men and 3 women) served as subjects in each test for a total of 804 subjects; no subject was used more than once during the study.

Subjects

The subjects were college students ranging in age from 18 to 23. All were volunteers and before participating in the experiment executed a subject release form. Each was paid $2.50 per h for participating.

Apparatus and Equipment

All testing took place in a 8 ft X 10 ft Sherer chamber whose interior had been modified with wood paneling, carpeting, and pole lamps. The room was equipped with a portable toilet, a table and six comfortable chairs for the subjects. Water was available for the subjects upon demand.

Each subject was provided with two ballots: a nine category thermal sensation scale and a seven category semantic differential comfort scale. These scales are shown in Fig. 1. Three thermistors were used to measure the subject's skin temperature.

Because Wyon has demonstrated that subjects who performed mental work had wider temperature tolerences than those who were resting, the subjects performed tasks involving anagrams, "seek and find" word games, "5 way" tic-tac-toe, simple arithmetic, "crossing off letters" and computed their own weighted mean skin temperature.

Each subject was provided with a standard clothing ensemble consisting of a cotton twill shirt and trousers which for the male subjects was worn over undershorts or jockey shorts and for the women was worn over a brassiere and panties. Cotton socks and sandals completed the ensemble whose insulation value was 0.6 clo. Each subject was provided with a simple computer for calculating his weighted mean skin temperature.

Procedure

The subjects reported for the test in groups of six and if their oral temperatures were 98.6F $\pm$0.5F (37°C $\pm$.3°C) they disrobed. After the skin temperature sensors were attached to the left pectoral regions of the chest, the radial surface of the left arm and fibular surface of the left leg, the subjects dressed in the standard uniform noted above and were read the following orientation statement:

"The purpose of the study you are about to begin is to determine your response to the thermal environment. The way it will proceed is this: in about 30 min you will be taken into the test room and be seated for _____ h. While you are there you will be performing mental and manipulative tasks according to the instructions we give you. From time to time you will be asked to stand and stretch your legs; however, you cannot sleep nor leave the room during the test period. Each of you has two ballots, one for temperature and one for comfort. Looking at the white ballot headed temperature, select the adjective that describes how you feel and circle the number beside that adjective. Do this now. We would also like to learn your feelings about comfort. To do this refer to the other ballot (read the directions). Complete this now. Between votings we will ask you to perform certain mental tasks (describe each). In addition, you will be asked to make some simple computations on these sheets that will be passed to you in the room. Do you have any questions?"

After approximately 30 min in the pre-test room which was maintained at 74F (23.3°C) the subjects entered the chamber, and the test began. The activities noted above occured at the times indicated and votes were recorded and skin temperatures were taken after the subjects had been in the chamber for 30 min and once every 10 min thereafter. For the first 90 min, the $T_B$ was held constant; after this the temperature began to fluctuate according to the schedule in effect at the time. Upon completion of the test, the subjects changed back into their own clothes, were paid at the rate of $2.50 per hour and were dismissed.

## RESULTS

The weighted mean skin temperatures, Twmsk, were computed for each observation period according to the following formula:

$$Twmsk = 0.5\ t_{skc} + 0.36\ t_{sk\ell} + 0.14\ t_{ska}$$

where

Twmsk = weighted mean skin temperature

$t_{skc}$ = skin temperature measured at the chest

$t_{sk\ell}$ = skin temperature measured at the leg

$t_{ska}$ = skin temperature measured at the arm.

In addition, values ranging from 1 for uncomfortable to 7 for comfortable were assigned to the responses on the comfort ballot. Then the mean value of these together with the mean thermal sensations were computed for each ten minute observation period. These values were also plotted for each test and were examined for inconsistencies and missing data. Examples of the plots for tests 77 and 78 of Condition 20 (79F + 5F @ 4F/h; 79F - 5F @ 4F/h) and tests 79 and 80 (79F - 5F @ 4F/h; 79F + 5F @ 4F/h) are presented in Figures 2, 3, and 4, for the thermal sensation vote, thermal comfort vote, and weighted mean skin temperatures, respectively. Following this, four critical points during the tests were selected for study. These were the times that while the temperature was fluctuating upward (1) the highest temperature was reached and (2) the lowest temperature was reached; and the time that the temperature was fluctuating downward when (3) the lowest temperature was reached and (4) when the highest temperature was reached. These are identified as follows:

a+ time when the temperature which was increasing from the basal temperature reached its maximum.

a- the time after a+ when the fluctuating temperature reached its minimum.

d- the time when the temperature which was decreasing from its basal temperature reached its minimum.

d+ the time after d- when the fluctuating temperature reached its maximum.

These critical points are more readily understood from the schematic representation in Fig. 5. At each of these points the mean thermal sensation vote was determined. Then using the procedure outlined by Cochran and Cox, regression equations were developed.

These are presented in Table 1 for the Thermal Comfort Votes, Table 2 for Thermal Sensation Votes, and Table 3 for the Weighted Mean Skin Temperatures. The regression equations were then used to predict the thermal sensations from basal temperatures ($T_B$) ranging from 60 FET* (15.6°CET*) to 98 FET* (36.7°CET*) in 2F (1.1°C) increments for amplitudes (A) of 2, 4, 6, 8, and 10F (1.1, 2.2, 3.3, 4.4 and 5.6°C) and $r_1$ values of 2, 4, and 6F/h (1.1, 2.2 and 3.3°C/h) and $r_2$ values of 2, 4, and 6F/h (1.1, 2.2 and 3.3°C/h). The same procedure was repeated for the thermal comfort (TC) values.

When these eight values were obtained (4-TS values for a+, a-, d-, and d+ and 4-TC values for a+, a-, d-, and d+) the conditions were identified in which all of the predicted TS values would fall between 4.0 and 6.0. This range was selected because it was estimated that a substantial majority of the people (estimated 73%, Fanger, 1970) would be comfortable in these conditions. This analysis showed that none of the conditions which was identified as being comfortable had basal temperatures that were either increasing or decreasing at rates that were greater than 6F/h (3.3°C/h) nor had peak-to-peak amplitudes which were greater than 6F (±3.3°C). Of the conditions that <u>were</u> acceptable for comfort, all had basal temperatures which had peak-to-peak amplitudes of 6F (3.3°C) or less and fluctuating rates of equal or less than 6F/h (3.3°C/h). The thermally acceptable cyclical conditions are presented in Table 4.

The ASHRAE Comfort Standard, 55-74, states that the rate of change in dry bulb temperatures should not exceed 4F/h (2.2°C/hr) if the peak-to-peak swing in dry bulb temperature is 2F (1.1°C) or greater during each cycle. Examination of Table 4 provides only partial support for this statement since rates as high as 6F/h (3.3°C/h) are evident as well as amplitudes 6F (3.3°C). Because of this, it is suggested that the non-steady state portion of the Standard reflect this finding. Specifically, it should state that for humans engaged in near-sedentary activities while wearing light clothing, it the temperature conditions for comfort are met, the thermal environment will be <u>acceptable</u> if (a) the rate of change does not exceed 6F/h (3.3°C/h) and (b) the <u>peak-to-peak</u> amplitude is equal or less than 6F or ±3F (3.3°C or ±1.6°C).

When cylical fluctuations are considered in energy conservation terms, the question arises concerning the extent to which the temperature could drift in and out of the comfort zone without affecting comfort. The data in Table 4 suggest that when the temperature is fluctuating at a slow rate, 2F/h (1.1°C/h), comfort can be maintained as low as 71F (21.7°C), a temperature lower than that usually considered as comfortable for the clothing and activity levels involved in this study. The opposite is true when the rate of fluctuation is high, 6F/h (3.3°C), where comfort can be experienced at temperatures as high as 83F (28.3°C).

In a different approach, point a+ in the acending mode was considered as the maximum point of a "ramp" condition in which the temperature was drifting upward from the basal temperature at a given hourly rate. Conversely, point d- in the descending mode was considered as the minimum point in a downward-moving ramp condition in which the basal temperature was decreasing at a given hourly rate. Using equation [5] the thermal sensation (TS) was estimated for the maximum value in the ascending mode, a+, when the basal temperatures ranged in 2F (1.1°C) increments from 60F (15.6°C) to 76F (24.4°C) with $r_1$ values of 1, 2, 4, and 8F/h (0.6, 1.1, 2.2, and 4.4°C/h). Table 5 presents conditions in which the TS would not exceed a value of 6 (slightly warm). For the descending ramps, d- values were estimated from equation [7] for basal temperatures ranging in 2F (1.1°C) increments from 98F (36.7°C) to 70F (21.1°C) with $r_1$ values of -1, -2, -4, and -8F/h (-0.6, -1.1, -2.2, and -4.4°C/h); similarly, the conditions were identified which the TS would not be less than 4.0 (slightly cool). These are presented in Table 6. From this procedure we must conclude that predicting the thermal sensation from a given temperature may result in different values depending upon "how" we arrived at the condition.

This exercise also permits an additional conclusion, namely, that going down to a given temperature under a descending ramp condition does not result in the same thermal sensation as going up to the same temperature in an ascending ramp. This is illustrated in the following example which predicts for 74F (23.3°C) TS values ranging from 4.0 (slightly cool) to 6.0 (slightly warm).

| A $T_B$ of | Fluctuating at the Rate of | Will be 74F in | At which time the TS will be |
|---|---|---|---|
| 66F | +8F/h | 1 h | 5.0 |
| | +4F/h | 2 h | 5.6 |
| | +2F/h | 4 h | 5.9 |
| | +1F/h | 8 h | 6.0 |
| 82F | -8F/h | 1 h | 4.0 |
| | -4F/h | 2 h | 4.2 |
| | -2F/h | 4 h | 4.4 |
| | -1F/h | 8 h | 4.4 |

## Discussion

While the temporal dimension has always been considered to be a factor in determining thermal comfort its role has been only secondary. However, with the findings reported in this paper, together with those by Rohles and Wells (2) and Berglund and Gonzales (3) the time variable obviously must be considered as a "qualifying" factor in all research in thermal comfort. By this we mean, the question related to an individual's response to a given set of thermal conditions must be: what was happening to the individual in terms of his thermal exposure prior to making that response? The posing of this question is based on the finding that a given temperature, as exemplified earlier in the case of 74F (23.3°C) may be accompanied by responses ranging from slightly cool (4) through neutral (5) to slightly warm (6). This must be compared to the prediction response of 3.3 (between slightly cool (3) and comfortable (4) on the seven category scale) from the Rohles and Nevins (9) comfort model

$$TS = .1509T + .0100H - 8.3709$$

where: T = air temperature; H = relative humidity; and TS = thermal sensation in which 1 = cold, 2 = cool, 3 = slightly cool, 4 = comfortable, 5 = slightly warm, 6 = warm, 7 = hot.

The study also must be examined from the standpoint of procedure. The recording of votes every 10 min is unique and indeed the way in which the votes paralleled the temperature fluctuation provides evidence that the methodology and controls were valid. The incorporation of the mental tasks also are believed to be procedural feature that should be included in future tests.

In conclusion, then, the limits of cyclical temperature fluctuation for comfort have been specified. In addition acceptable ramp conditions have been suggested. These constitute models that are based on empirical tests; their validation is suggested as the next step to further understand the temporal feature of man's response to his thermal environment.

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Table 1. Regression equations for predicting thermal comfort (TC)* and accompanying multiple correlation coefficients (R)

| R | Regression Equation | |
|---|---|---|
| .70 | $TC/a+ = +11.263 - .100\ T_B - .102\ A + .253\ r_1$ | [1] |
| .52 | $TC/a- = 1.332 + .058\ T_B + .023\ A + .038\ r_1 + .205\ r_2$ | [2] |
| .53 | $TC/d- = -.428 + .052\ T_B - .052\ A + .264\ r_1$ | [3] |
| .64 | $TC/d+ = +11.693 - .092\ T_B - .087\ A - .027\ r_1 - .048\ r_2$ | [4] |

*TC/a+ (Thermal Comfort; mode: ascending; temperature: maximum)
TC/a- (Thermal Comfort; mode: ascending; temperature: minimum)
TC/d- (Thermal Comfort; mode: descending; temperature: minimum)
TC/d+ (Thermal Comfort; mode: descending; temperature: maximum)

$T_B$ = basal temperature - F
A = amplitude - peak to peak in F
$r_1$ = initial rate F/h
$r_2$ = subsequent rate F/h

Table 2. Regression equations for predicting thermal sensation (TS)* and accompanying multiple correlation coefficients (R)

| R | Regresion Equation | |
|---|---|---|
| .94 | $TS/a+ = -8.673 + .183\ T_B + .172\ A - .149\ r_1$ | [5] |
| .96 | $TS/a- = -6.921 + .162\ T_B - .228\ A - .178\ r_1 + .212\ r_2$ | [6] |
| .94 | $TS/d- = -6.703 + .153\ T_B - .085\ A - .065\ r_1$ | [7] |
| .94 | $TS/d+ = -9.395 + .192\ T_B + .137\ A - .121\ r_1 + .045\ r_2$ | [8] |

*TS/a+ (Thermal Sensation; mode: ascending; temperature: maximum)
TS/a- (Thermal Sensation; mode: ascending; temperature: minimum)
TS/d- (Thermal Sensation; mode: descending; temperature: minimum)
TS/d+ (Thermal Sensation; mode: descending; temperature: maximum)

$T_B$ = basal temperature - F
A = amplitude - peak to peak in F
$r_1$ = initial rate F/h
$r_2$ = subsequent rate F/h

Table 3. Regression equations for predicting weighted mean skin temperatures (Twmsk)* and accompanying multiple correlation coefficients (R)

| R | Regression Equations | |
|---|---|---|
| .96 | Twmsk/a+ = 69.681 + .287 $T_B$ + .145 A .045 $r_1$ | [ 9] |
| .96 | Twmsk/a- = 65.840 + .331 $T_B$ .070 A + .006 $r_1$ + .078 $r_2$ | [10] |
| .95 | Twmsk/d- = 67.152 + .330 $T_B$ .202 A + .031 $r_1$ | [11] |
| .96 | Twmsk/d+ = 67.232 + .327 $T_B$ .003 A .048 $r_1$ + .018 $r_2$ | [12] |

*Twmsk/a+ (Weighted Mean Skin Temperature; mode: ascending; temperature: maximum)

Twmsk/a- (Weighted Mean Skin Temperature; mode: ascending; temperature: minimum)

Twmsk/d- (Weighted Mean Skin Temperature; mode: descending; temperature: minimum)

Twmsk/d+ (Weighted Mean Skin Temperature; mode: descending; temperature: maximum)

$T_B$ = basal temperature - F

A = amplitude - peak to peak in F

$r_1$ = initial rate F/h

$r_2$ = subsequent rate F/h

Table 4. Thermally acceptable cyclical conditions (A)* for humans engaged in near-sedentary activity while dressed in light clothing

| Range of Temperature Fluctuations (F) | $r_2$(F/h) | $r_1$ = 2F/h | | | $r_1$ = 4F/h | | | $r_1$ = 6F/h | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | 2 | 4 | 6 | 2 | 4 | 6 | 2 | 4 | 6 |
| 82 ± 1 | | - | - | - | - | - | - | A | - | - |
| 80 ± 1 | | - | - | - | A | A | - | A | A | A |
| ± 2 | | - | - | - | - | - | - | A | A | - |
| 78 ± 1 | | - | A | A | A | A | A | A | A | A |
| ± 2 | | - | - | - | A | A | A | A | A | A |
| ± 3 | | - | - | - | A | - | - | - | A | A |
| 76 ± 1 | | A | A | A | A | A | A | A | A | A |
| ± 2 | | - | - | A | A | A | A | - | A | A |
| ± 3 | | - | - | - | - | A | A | - | - | A |
| 74 ± 1 | | A | A | A | A | A | A | A | A | A |
| ± 2 | | - | A | A | - | A | A | - | - | - |
| ± 3 | | - | - | A | - | - | - | - | - | - |
| 72 ± 1 | | A | A | A | - | - | - | - | - | - |

* Acceptable conditions (A) have Mean Predicted Thermal Sensations (TS) Votes as averaged at points a+, a-, d- d+ of slightly cool (4), neutral (5), or slightly warm(6) and Mean Predicted Thermal Comfort (TC) Votes at the same points of 4.0 or greater. The range of temperature fluctuations vary according to the basal temperature, but the peak-to-peak amplitude never exceeds 6F (±3F); rates greater than 6F/h are unacceptable regardless of basal temperature and amplitude.

Table 5. Ascending ramp conditions for comfort*

| A $T_B$ of | Increasing at the hourly rate (F) | *Can maintain comfort for Hrs. | Min. | At which time the temperature will be |
|---|---|---|---|---|
| 70F | 2F/h | 3 | 00 | 76.0 |
| | 1 | 5 | 45 | 75.8 |
| 72F | 8 | 1 | 00 | 80.0 |
| | 4 | 1 | 30 | 78.0 |
| | 2 | 2 | 00 | 77.0 |
| | 1 | 4 | 45 | 76.8 |
| 74F | 8 | 0 | 45 | 80.0 |
| | 4 | 1 | 15 | 79.0 |
| | 2 | 2 | 00 | 78.0 |
| | 1 | 3 | 45 | 77.8 |
| 76F | 8 | 0 | 30 | 80.0 |
| | 4 | 1 | 00 | 80.0 |
| | 2 | 1 | 30 | 79.0 |
| | 1 | 3 | 45 | 78.8 |
| 78F | 8 | 0 | 30 | 82.0 |
| | 4 | 0 | 45 | 81.0 |
| | 2 | 1 | 00 | 80.0 |
| | 1 | 1 | 30 | 79.5 |
| 80F | 8 | 0 | 15 | 82.0 |
| | 4 | 0 | 15 | 81.0 |
| | 2 | 0 | 30 | 81.0 |
| | 1 | 0 | 30 | 80.5 |

*Will not exceed a TS vote of 6.0

Table 6. Descending ramp conditions for comfort

| A $T_B$ of | Decreasing at the hourly rate (F) | *Can maintain comfort for Hrs. | Min. | At which time the temperature will be |
|---|---|---|---|---|
| 88F | 8F/h | 1 | 30 | 76.0 |
| 86F | 8 | 1 | 15 | 76.0 |
| | 4 | 3 | 15 | 73.0 |
| 84F | 8 | 1 | 00 | 76.0 |
| | 4 | 2 | 45 | 73.0 |
| | 2 | 6 | 00 | 72.0 |
| | 1 | (a) 8 | 00 | (4.7) 76.0 |
| 82F | 8 | 1 | 00 | 74.0 |
| | 4 | 2 | 15 | 73.0 |
| | 2 | 5 | 00 | 72.0 |
| | 1 | (b) 8 | 00 | (4.4) 74.0 |
| 80F | 8 | 0 | 45 | 74.0 |
| | 4 | 1 | 45 | 73.0 |
| | 2 | 4 | 00 | 72.0 |
| | 1 | (c) 8 | 00 | (4.1) 72.0 |
| 78F | 8 | 0 | 30 | 74.0 |
| | 4 | 1 | 30 | 72.0 |
| | 2 | 3 | 15 | 71.5 |
| | 1 | 7 | 00 | 71.0 |
| 76F | 8 | 0 | 15 | 74.0 |
| | 4 | 1 | 00 | 73.0 |
| | 2 | 2 | 15 | 71.5 |
| | 1 | 5 | 15 | 70.8 |
| 74F | 4 | 0 | 30 | 72.0 |
| | 2 | 1 | 30 | 71.0 |
| | 1 | 3 | 30 | 70.5 |
| 72F | 2 | 0 | 30 | 71.0 |
| | 1 | 1 | 45 | 70.3 |

(a at 8 h, TS=4.7; (b) at 8 h, TS=4.4; (c) at 8 h, TS=4.1

*Will not have a TS lower than 4.0

Circle the number beside the adjective that describes how you feel.

9 very hot
8 hot
7 warm
6 slightly warm
5 neutral
4 slightly cool
3 cool
2 cold
1 very cold

Place a check on the line that describes how comfortable or uncomfortable you feel.

uncomfortable ___:___:___:___:___:___:___ comfortable

*Fig. 1 Thermal sensation and thermal comfort ballots*

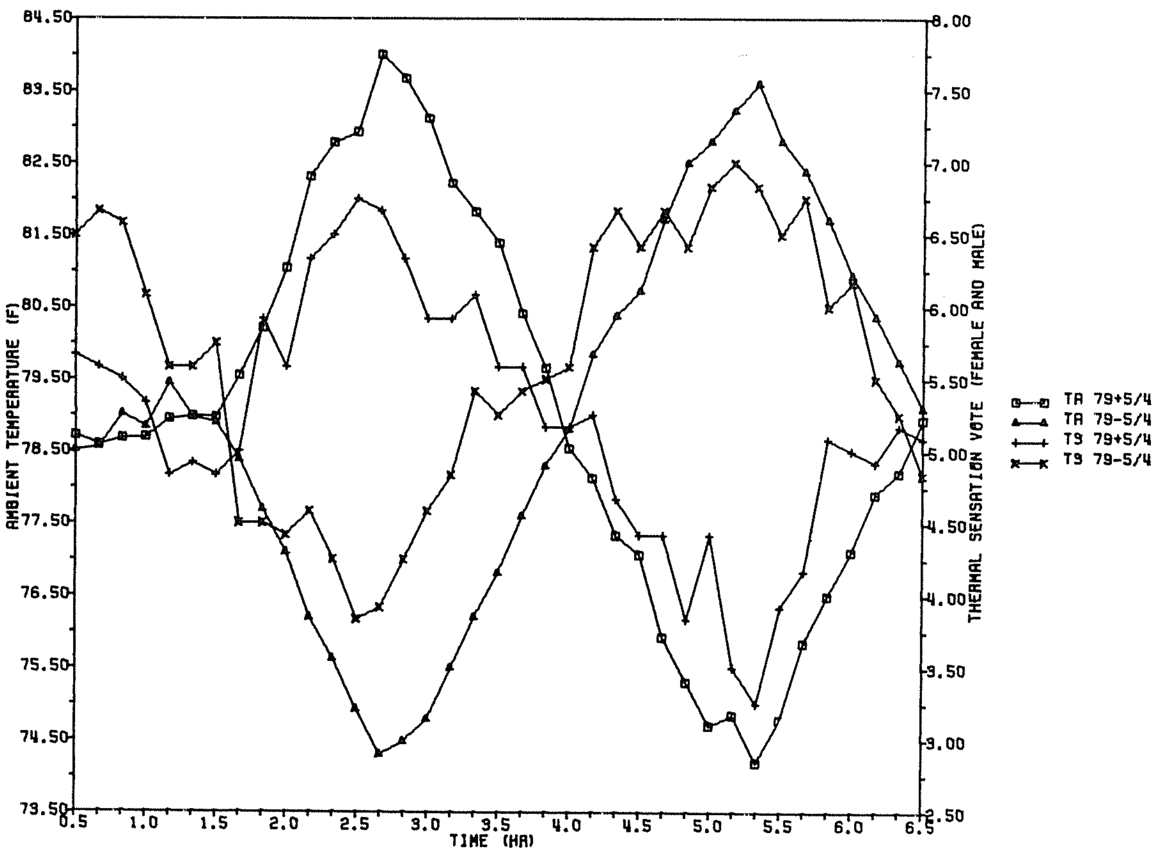


*Fig. 2 Thermal sensation votes (TS) under two ambient temperature cycles (TA) 79 F + 5 F @ 4 F/h; 79 F - 5 F @ 4 F/h*

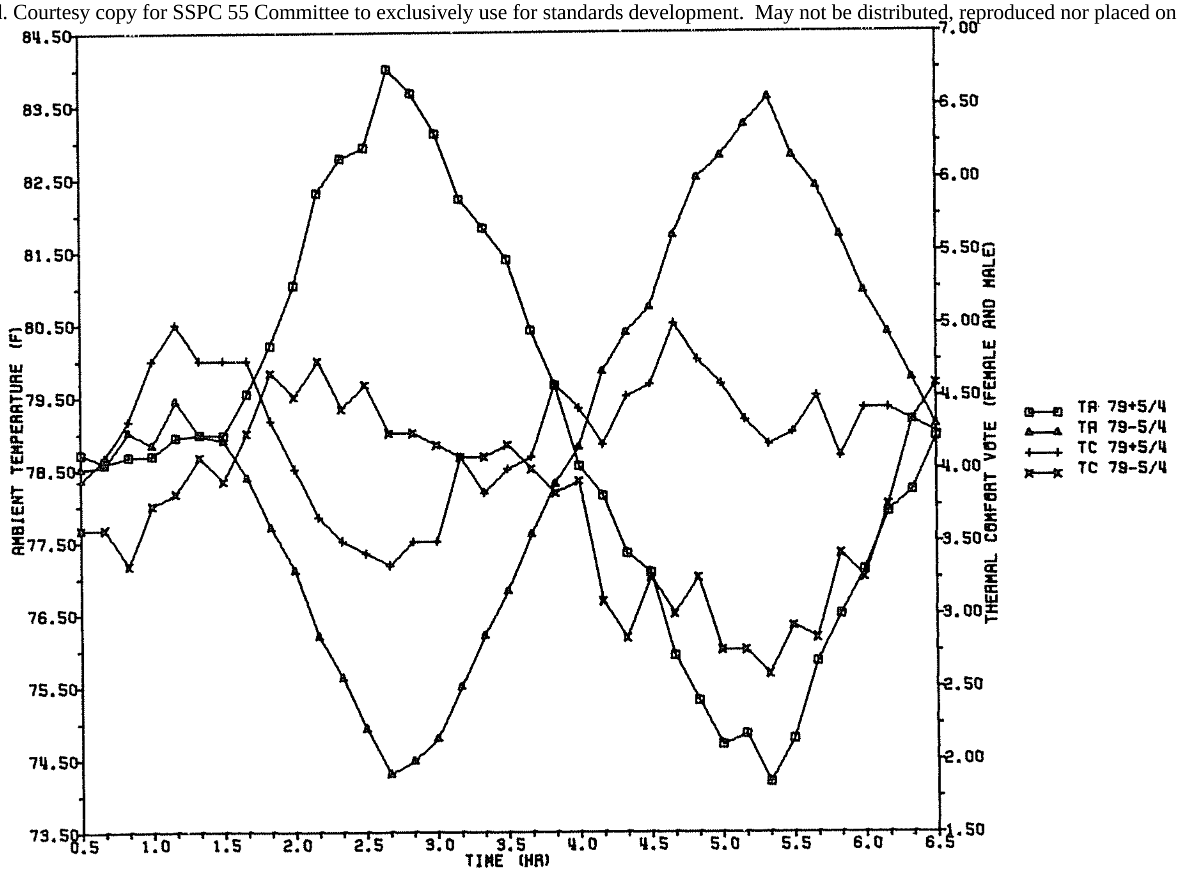


*Fig. 3 Thermal comfort votes (TC) under two ambient temperature cycles (TA) 79 F + 5 F @ 4 F/h; 79 F - 5 F @ 4 F/h*

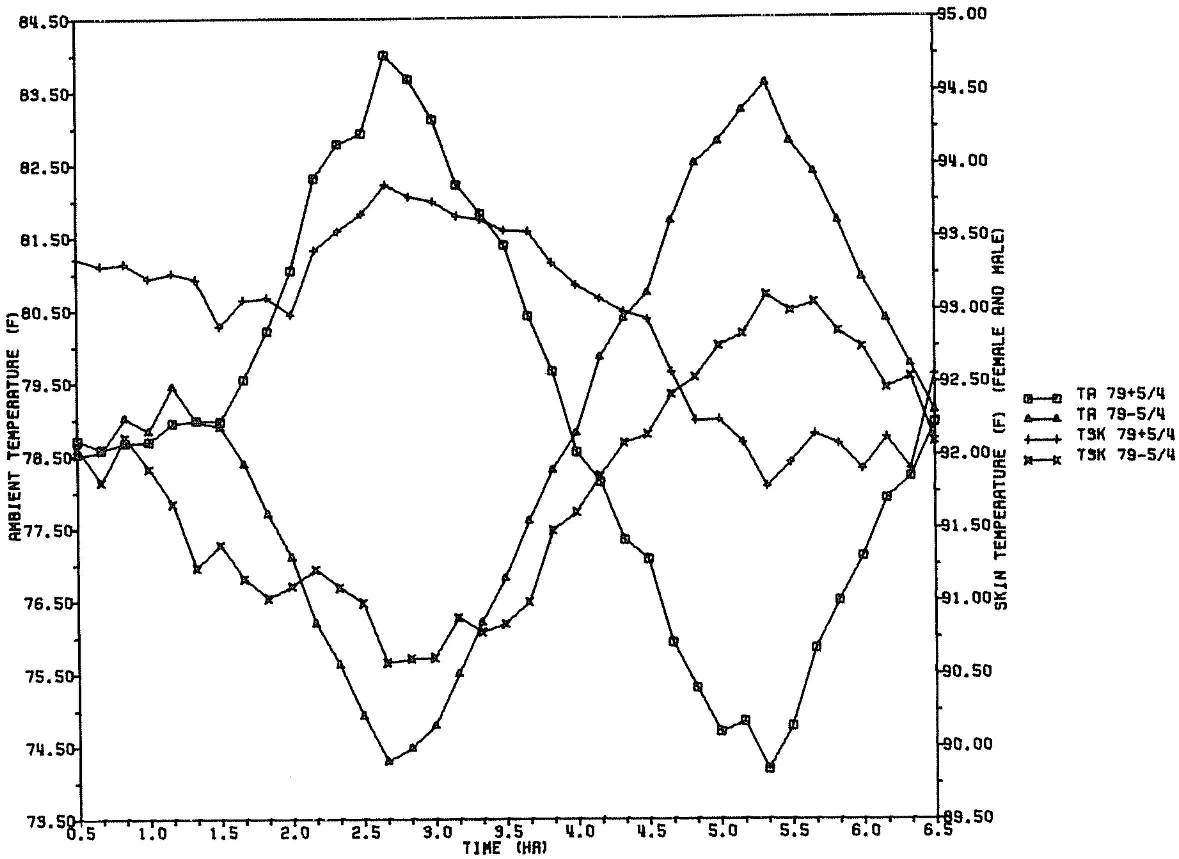


*Fig. 4 Weighted mean skin temperature (TSK) under two ambient temperature cycles (TA) 79 F + 5 F @ 4/h; 79 F - 5 F @ 4 F/h*

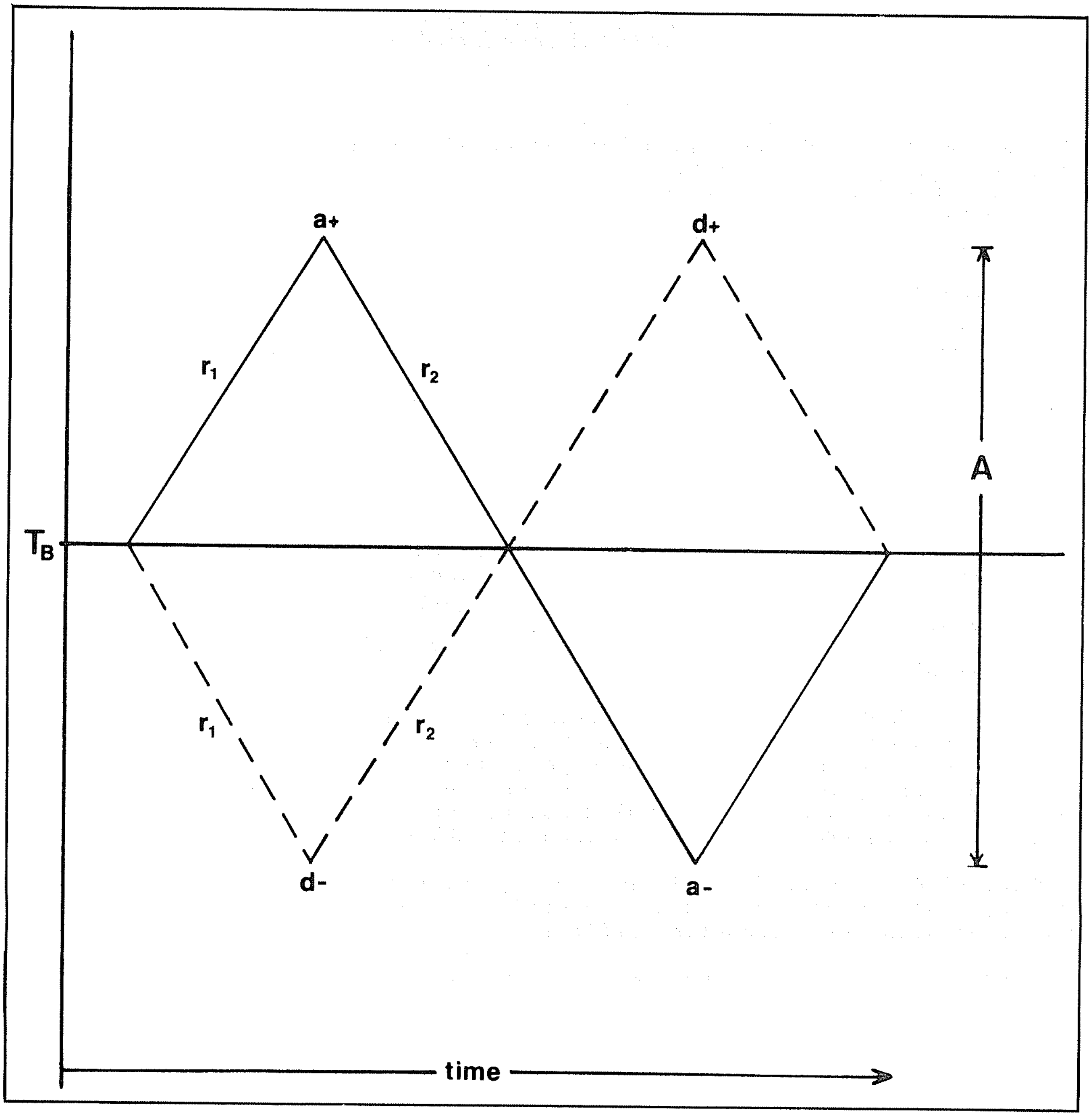


*Fig. 5 Schematic representation of the conditions of the cyclical study (see text for details)*

# DISCUSSION

P.O. FANGER, Prof., D. Sc., Technical Univ. of Denmark, Lab. of Heating & Air Conditioning, Lyngby, Denmark: Dr. Rohles and his associates should be complimented for the completion of these comprehensive experiments. A fine collection of raw data on the human response to changing ambient temperatures are now available. However, I am not sure that I agree with your analysis and conclusion.

1) In comparing to ASHRAE Standard 55-74, you specify a comfort interval of -14.4°C (6 F) 22.2-25.6°C (72-78 F). This corresponds approx. to 1.0 vote (±0.5) in your steady-state prediction model (or on the PMV-model). May I suggest that the same criteria be used when analyzing your dynamic data, i.e. use ±0.5 votes, not ±1 vote as you have done in this paper. If this is done, your data show that man is much more sensitive to cyclical temperature fluctuations (or ramps) than earlier anticipated: He accepts less than half of the temperature range that would be felt acceptable during steady-state conditions.

2) In the paper, you do not mention anything about the mean radiant temperature. Due to the heat capacity of the walls, floor, and ceiling the MRT will be delayed and damped when the air temperature cycles. If the information is not available, may I suggest that you measure or calculate the mean radiant temperature for a few characteristic temperature cycles of the present study and include this information in the discussion of this paper.

FREDERICK H. ROHLES, Jr.: I think your point on acceptance is well taken. However, remember we used a 9 category scale in this study as compared to a 7 category scale in the steady-state experiments. The air temperature and MRT were equal during the first 90 min. of the exposure. That the MRT could be delayed during the runnings is a valid point. However, our subjects were seated at least a metre from the wall; as such the MRT would have only minor influence.

DR. D.J. FISK, Head of Mech. & Elec. Div., Building Resch. Establishment, Watford, UK: May I add my congratulations to Professor Rohles for a major contribution in an area with great semantic difficulties.

In Wyon's work (Ref 1) the occupants only voted when prompted by the thermal environment. To what extent is it possible to reject the hypothesis that the time dependence observed in this paper might be due to the influence on the subject of his knowledge of his previous votes, especially in the context of a slowly varying and diffuse stimulus?

ROHLES: As we discussed this question earlier in detail, I believe that your point is well taken that voting every 10 min. might cause an individual to pay more attention to his thermal environment than under normal conditions. Of course we collected the ballots on which the subjects responded after each voting period. However, they still could have recalled their response of 10 min. previous. I have to believe, however, that a continuing condition of attending to when a change in temperature occurs may be similarly criticized. Unfortunately we have no alternative to the ballotry procedure.