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THE EFFECTS OF AIR MOVEMENT AND TEMPERATURE ON THE THERMAL SENSATIONS OF SEDENTARY MAN

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The effect of wind on the behavior of living organisms is difficult to describe. At low temperatures its noxious qualities cause sled dogs to roll up in a ball, domestic and wild animals alike to seek shelter, and men to raise their coat collars and turn their backs in the direction from which the wind is blowing. In summer, high winds signalling the approach of a thunderstorm send birds and farm animals into hiding. And even before the cooling effects of high-velocity air are felt under automobile airconditioning, a universal practice of reducing the blower speed is observed.

From empirical studies with animals, it has been hypothesized that all winds of 880 ft/min (10 mph) are unpleasant regardless of temperature and that winds of 440 ft/min (5 mph) and less have a differential affectivity in that they are unpleasant at high and low temperatures and pleasant under comfortable or moderate thermal conditions. The test of this hypothesis has been conducted with non-human primates; however, its support from human subjects has only been conjectured (1,2,3). Thus, the purpose of this study was to determine the affectivity or thermal sensations of sedentary human subjects when exposed to various conditions of air movement at different ambient temperatures.

DESIGN

Air movements of three velocities were selected for study: 40, 80, and 160 ft/min, and were employed at each of the following three temperatures: 72.0, 78.6, and 85.2 F, for a total of 9 (3 x 3) experimental conditions. These temperatures were derived by solving the following equation for T (Temperature F) when the relative humidity (H) was 50 and Y (the thermal sensation) was equal to 3 (slightly cool), 4 (comfortable), and 5 (slightly warm):

$$Y = .151\ T + .010\ H - 8.371 \qquad [1]$$

This is the regression equation developed by Rohles and Nevins (4) for predicting the thermal sensation Y for a given temperature and relative humidity for men and women combined after an exposure of 3 hours.

SUBJECTS

The subjects consisted of 90 college-age students--45 men and 45 women--who were exposed in groups of 5 to the 9 experimental conditions for 3 hours. All were volunteers and were paid $5.00 for participating.

FACILITIES AND EQUIPMENT

All tests were conducted in an 8 x 12 ft room that was constructed in the 12 x 24 ft KSU-ASHRAE chamber. A cut-away drawing of this room is shown in Fig. 1. The walls of the room were constructed of 1/4 in. plywood and ran from the ceiling to within 4 in. of the floor; this space served as the outlet for the "return-air." Two 30 in. doors at opposite ends of the walls were provided as shown in the figure. These walls were placed flush against the side walls of the ASHRAE chamber so that the end walls of the room (8 ft dimension) were actually the walls of the ASHRAE chamber. The ceiling consisted of 6 adjoining ducts which were 24 in. wide, 8 in. deep, and 8 ft long. Three of the ducts terminated in a plenum on one side of the room and the other three ducts terminated in a plenum on the opposite side of the room. The base of each duct, which was the ceiling of the room, was constructed from

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3/8 in. fiberboard perforated with 1/4 in. holes to provide an approximate 20% net opening of the ceiling cross-section. Above this perforated fiberboard, and resting on it, was a 1/4 in. layer of open-cell expanded polyurethane filter material (Kimberly-Clark Scottfoam). This combination of filter material and perforated ceiling permitted a uniform air distribution throughout the room at the flow rates under study.

The air flow was generated by four double-inlet 15 in. forward curve centrifugal blowers (Lau Model 15-15/AC), which were spring-mounted on the chamber floor outside the room. Two of the blowers were on each side of the room and supplied air to their respective plenums through flexible canvas ducts. The noise levels for the 40, 80, and 160 ft/min conditions were 53, 58, and 63 db(A), respectively, as measured at 2 ft above the floor with General Radio Model 1551B sound level meter.

Equally spaced and surface-mounted on the perforated ceiling were three double-tube fluorescent light fixtures which gave 150 ft-candles of illumination at desk height.

Five tablet-arm chairs were provided for the subjects.

Three skin-temperature thermistors (Yellow Springs Series 409) were given each subject. These were placed on the subject's chest, forearm and calf, and were connected to a junction box in the center of the room from which they ultimately terminated at an automatic scanner and digital thermometer and recorder (Digitec, United Systems Corp.).

Three ballots were used to obtain the dependent measures. The first was the traditional thermal sensation ballot which contained the following vertical listing of numbers and adjectives: 1, cold; 2, cool; 3, slightly cool; 4, comfortable; 5, slightly warm; 6, warm; 7, hot. The second ballot, which was designed to measure the subjects' responses to the air movement, consisted of a seven-point adjective rating: 1, very unpleasant; 2, unpleasant; 3, slightly unpleasant; 4, neutral; 5, slightly pleasant; 6, pleasant; 7, very pleasant. The third designed to measure the responses of the subjects to sound, also consisted of a seven-point adjectival rating: 1, very quiet; 2, quiet; 3, somewhat quiet; 4, neutral; 5, slightly noisy; 6, noisy; and 7, very noisy.

PROCEDURE

The subjects reported for the tests in groups of 5 males or 5 females and if their oral temperatures were within the range of 98.6 F ± 0.4 F, they removed all of their clothing except their underwear. After attaching skin temperature thermistors to the left pectoral region of the chest, the radial surface of the left arm, and the fibular surface of the left leg, the subject donned the Standard KSU Uniform and cotton socks. This consists of a cotton-twill shirt and trousers and is similar to the types of uniforms worn by service station attendants. The insulation value of the uniform when worn over jockey shorts or a bra and panties is 0.6 clo.

When all of the subjects were dressed, they were instructed concerning the purpose of the tests, the procedures that would be followed, and the rules of conduct during the exposure. After approximately 45 min. in the neutral 78 F environment of the pre-test room, they entered the test room and were seated in the chairs provided. The test lasted 3 hours.

After one hour, and every half hour thereafter, votes were taken on the thermal sensation ballot. Votes on the noise and air-movement ballots were taken after 1, 2, and 3 hours, and in all of the voting the ballots were collected after each recording so they could not be referred to on subsequent votes. After 10 minutes, and every 10 minutes thereafter during the 3-hour exposure period, the skin temperatures of the subjects were recorded.

When the test was finished, the subjects changed back into their street clothes, were paid and dismissed.

RESULTS

Thermal Sensations

Means of the five thermal sensation votes for the men, women, and men and women combined were computed. These are presented in Table 1. In addition the votes were treated by analysis of variance for a 3 x 3 x 2 (temperature, air movement level, sex) factorial design with repeated measures. This procedure showed a significant difference in the voting

Table 1. MEAN HOURLY THERMAL SENSATIONS FOR MALES, FEMALES, AND MALES AND FEMALES COMBINED AT THREE TEMPERATURES (F) AND THREE AIR MOVEMENT LEVELS (ft/min)

F/ft-min	Exposure (hrs)				
	1.0	1.5	2.0	2.5	3.0
Males (N=45)					
72.0/40	4.2	3.8	3.8	3.8	3.6
78.6/40	4.4	4.6	4.4	4.2	4.0
85.2/40	5.4	4.2	4.8	5.2	4.6
72.0/80	3.2	3.0	2.2	2.0	2.0
78.6/80	3.6	3.8	3.6	3.4	3.8
85.2/80	5.2	5.2	4.8	4.8	4.6
72.0/160	2.8	2.6	2.6	3.2	3.0
78.6/160	3.0	3.8	3.6	3.8	3.2
85.2/160	5.0	4.2	4.4	4.4	4.4
Females (N=45)					
72.0/40	3.6	3.2	4.0	3.2	2.4
78.6/40	4.4	4.0	4.6	4.8	4.6
85.2/40	5.4	4.6	5.0	5.0	4.8
72.0/80	2.6	2.6	2.4	2.4	1.8
78.6/80	3.4	3.2	2.6	3.4	3.6
85.2/80	5.8	5.4	5.2	5.0	4.6
72.0/160	2.2	2.2	2.6	2.4	2.4
78.6/160	3.8	3.0	3.6	3.0	3.6
85.2/160	5.6	5.0	5.0	4.8	4.6
Males and Females (N=90)					
72.0/40	3.9	3.5	3.9	3.5	3.0
78.6/40	4.4	4.3	4.5	4.5	4.3
85.2/40	5.4	4.4	4.9	5.1	4.7
72.0/80	2.9	2.8	2.3	2.2	1.9
78.6/80	3.5	3.5	3.1	3.4	3.7
85.2/80	5.5	5.3	5.0	4.9	4.6
72.0/160	2.5	2.4	2.6	2.8	2.7
78.6/160	3.4	2.4	2.6	2.8	3.4
85.2/160	5.3	4.6	4.7	4.6	4.5

periods ($F = 5.836$; df 4/449; $P < 0.001$) and when the means for the combined men and women were examined for each of the 5 voting periods, they demonstrated the short-term, sensory-type adaptation that has been observed in previous studies of the thermal sensation. These values were 4.1, 3.8, 3.8, 3.8, and 3.6 for the five respective voting periods.

The variances attributable to temperature and air-movement and the temperature by air-movement interaction were also highly significant. The F ratios for these effects were: temperature, $F = 80.768$, df 2/449, $P < .001$; air movement, $F = 11.605$, df 2/449, $P < .001$; temperature x air-movement, $F = 3.321$, df 4/449, $P < .02$. The variances attributable to the temperature by vote, air movement by vote, and temperature by air movement by vote, each had an F-ratio which was significant at the 2% level of confidence. The variances attributable to sex were not significant ($P > 0.50$); this finding represents a significant deviation from the results of similar studies in which sex differences were observed. The mean thermal sensations for the three air temperatures are presented graphically in Fig. 2 for each of the three air movement conditions. With reference to the 40 ft/min curve, at 72 F the mean thermal sensation was 3.0 (slightly cool) which is the thermal sensation predicted from equation [1], above. However, the predicted thermal sensation of comfortable was <u>below</u> the observed thermal sensation at 78.6 F (4.0 as compared with 4.3), and the predicted value of

5.0 (slightly warm) was above the observed sensation (4.7) at 85.2 F. Since the standard error of estimate of Eq. [1] is 0.44, deviations of the magnitudes observed in this study must be expected, especially when considering the differences in room size and number of subjects tested compared to the original study upon which Eq. [1] was based.

Clearly, the 40 ft/min responses were above the responses of the other two air-movement conditions and both of these curves (Fig. 2), while similar, demonstrate the cooling effects of increased air-movement. Moreover, since the analysis of variance detected significant differences in thermal sensations due to temperature and air movement, Eq. [1] cannot be assumed to be valid at these higher air velocities. Therefore, a multiple regression equation for men and women combined after three hours' exposure was determined for the various temperatures and air velocities in this study at the constant relative humidity of 50%:

$$Y_{TS} = 0.157\ ET^* - 0.003\ V - 8.416 \qquad [2]$$

where

Y_{TS} = thermal sensation

ET^* = new ASHRAE Effective Temperature (F)

V = air movement (ft/min), where $V > 30$ ft/min

The multiple correlation coefficient was determined to be 0.704.

Sound Level Affectivity

The three responses to the sound during the 18 tests were also treated by analysis of variance in a 3 x 3 x 2 factorial design with repeated measures. As might be expected, the variances attributable to temperature were not significant ($P > .50$). However, a significant difference in the votes from the three voting periods was also observed for the responses to sound level. The means for the first, second, and third hour votes (4 = neutral; 5 = slightly noisy; 6 = noisy) were 4.5, 4.4, and 4.3, respectively, a finding which like the thermal sensation vote also exhibits an adaptation to the sound. The variance attributable to the air movement rates was also significant ($F = 16.676$; df 2/269; $P < 0.001$) and differences between the responses of the men and women were also observed ($F = 4.127$; df 1/269; $P < 0.05$). The mean votes for the men and women during exposures to the three air movement conditions [40 ft/min = 53 db (A); 80 ft/min = 58 db (A); and 160 ft/min = 63 db (A)] are presented graphically in Fig. 3. As indicated in this figure, very small sex differences were observed at the lower sound levels and the significant F-ratio for this variable is doubtlessly due to the wide separation of the mean votes during the 63 db (A), 160 ft/min condition. It is interesting to note, however, that none of the remaining variables was significant ($P > 0.10$), including sex by sound-level interaction.

Air-Movement Affectivity

Responses to the affectivity of the air movement itself were also treated by analysis of variance using a 3 x 3 x 2 factorial design with repeated measures. The variance attributable to the 3 observations after 1, 2, and 3 hours was statistically significant ($F = 2.890$; df 2/269; $P < 0.05$), a fact which provides evidence that adaptation is also occurring in this domain. Variance due to the main effect of temperature was also significant ($F = 3.773$; df 2/269; $P < 0.03$); and while the variance due to both air movement and sex was not statistically significant, the temperature by air movement interaction was highly so ($F = 5.997$; df 4; $P < 0.001$). The mean affective responses to the air movement under the three temperature conditions are presented in Fig. 4.

The reason for the significant temperature by air motion interaction is apparent from Fig. 4, since the sensation of pleasant air motion decreased as the temperature increased for the case of the lowest tested velocity of 40 ft/min, whereas the pleasant sensation increased with increasing temperatures for the air velocities of 80 and 160 ft/min.

Skin Temperatures

The weighted mean skin temperature for this study was determined by the following equation from Dr. Ralph Goldman (5):

$$t_{sk} = 0.5\ t_{skc} + 0.36\ t_{skl} + 0.14\ t_{ska} \qquad [3]$$

where

t_{sk} = weighted mean skin temperature

t_{skc} = skin temperature measured at chest

t_{ska} = skin temperature measured at arm

t_{skl} = skin temperature measured at leg

Once every ten minutes during the 3-hour tests, this value was determined for each subject, and was then treated by analysis of variance using the 3 x 3 x 2 factorial design for repeated measures. Whereas only a few of the variances were statistically significant in the other analyses, several were significant in the case of skin temperature. The first of these was the variance due to the 18 observations ($F = 49.387$; df 17/1619; $P < 0.001$). This finding again demonstrates that adaptation occurs during the course of the three-hour test. The variance in skin temperature attributable to both temperatures ($F = 144.829$; df 2/1619; $P < 0.001$) and air movement ($F = 23.307$; df 2/1619; $P < 0.001$) was significant. Two primary and two secondary interactions, all of which involved the observation (18 ten-minute readings) were also significant. These were temperature by observation ($F = 40.301$; df 34/1619; $P < 0.001$); air movement by observation ($F = 15.817$; df 34/1619; $P < 0.001$); temperature by air movement by observation ($F = 4.091$; df 68/1619; $P < 0.001$); and temperature by sex by observation ($F = 2.051$; df 34/1619; $P < 0.001$); the latter interaction was the only one involving sex which was statistically significant. The weighted mean skin temperatures are presented graphically in Fig. 5 for the three air movement conditions at each of the three temperatures during the three-hour test period. The results for the 78.6 F and 72.0 F conditions indicated that an increase in air movement was accompanied by a decrease in body temperature and this was more pronounced in the case of the 72.0 F condition than in the 78.6 F condition. Under all three temperature conditions, the mean skin temperature was highest in 40 ft/min condition. And while the 160 ft/min curve is consistently above the 80 ft/min curve at 85.2 F, little difference in the two curves is observed at the two lower temperatures.

DISCUSSION

An important consideration in the design of an environmental control system is the relative air movement in the occupied zone and its effect on the thermal sensation of the occupants. Following the development of the "old" effective temperature scale relating wet-bulb and dry-bulb temperatures to "thermal sensations", Houghten and Yaglou studied the cooling effect of various air velocities (6). A chart showing their results appeared in the ASHRAE Guide and Data Book until 1972. Morse and Kowalczewski (7) reported preferred air temperatures for thermal comfort based on heat transfer theory and published comfort data that included data from field experiments with velocities of 50, 100, and 170 ft/min. Fanger (8, p. 49) developed a mathematical model which predicts the comfort "vote" for the various environmental parameters. Olesen, Fanger, and Bassing (9) reported comfort conditions for two subjects at velocities of 160 ft/min and for two subjects at velocities of less than 20 ft/min. Gagge, Stolwijk, and Nishi (10) introduced a simple two-node model from which the amount of sweating at given environmental conditions can be predicted. Assuming thermal comfort exists at the threshold of regulatory sweating (PRSW = 0+), we have employed their model to predict "preferred temperatures" for the conditions outlined in Table 2 using convection heat transfer coefficients determined from the equation recommended by Fanger for forced convection (8, p. 36):

$$h_c = 10.4\sqrt{V} \quad ; \quad V > 0.1 \text{ m/s} \qquad [4]$$

where

h_c = confection heat transfer coefficient (kcal/hr m^2 C)

V = air velocity (m/s)

Data adapted from the references given above are shown in Table 2 and compared with the experimental results from this study for "comfortable" conditions. The conditions used to obtain the "preferred temperature" are not identical; however, the agreement is good in most cases. Velocities of 40 ft/min and lower are difficult to measure accurately and the air mass can have periods of instability. Also, as indicated previously, the standard error of estimate could explain much of the variation shown. At the higher velocities, Morse and Kowalczewski's model predicts relatively higher preferred temperatures. This may be due to

Table 2. PREFERRED AMBINET TEMPERATURES (DBT) FOR COMFORT (F)

$M = 400$ Btuh, $I_{cl} = 0.6$ clo, $t_{mrt} = t_a$, RH = 50%

Velocity ft/min	Velocity m/s	Gagge et al. (10)	Morse and Kowalczewski (7)	Fanger (8)	Houghten and Yaglou (6)	Olesen et al. (9)	This*** Study
20	0.1	75.2*	79.1	78.6	78.6	76.1	-
40	0.2	78.6**	81.5	80.0	80.0	-	80.4
80	0.4	80.5**	82.8	81.0	81.0	-	81.1
160	0.8	82.0**	84.1	82.0	82.5	79.2/79.7	82.7

*From two-node model as originally reported.

**From two-node model assuming (1) $h_c = 10.4\sqrt{V}$ for $V \geq 0.1$ m/s and (2) preferred temperature occurs at threshold of regulatory sweating (PRSW = 0+).

***Determined from Equation [2].

their definition of comfort (no sweating) and the assumption of a constant evaporative heat loss. Their field data confirmed the model but were for "clo" values of approximately 0.25. The values of Olesen et al. are lower than would be expected. These data were obtained with only two subjects at each condition. Their metabolic heat production was approximately 360 Btuh, while the estimated heat production for subjects in this study was 400 Btuh. The values determined from the two-node model of Gagge et al. (10) are close to those found in this study at the higher velocities and slightly lower at 40 ft/min. The "preferred temperatures" for the subjects tested in this experiment, as given in Table 2, were determined from Eq. 2 by setting $Y_{TS} = 4$ (comfortable) and solving for the dry-bulb temperature at 50%, (i.e. ET*).

The significant differences found in the main effects of temperature and air motion and in the temperature by air motion interaction imply that the effect of convection heat transfer may influence the affective response to air motion in addition to the thermal sensation. Since the subjects were all tested under sedentary conditions, and neither their positions nor the MRT were changed at the various velocities, a simple steady state heat transfer model can be developed by which the change in sensible heat transfer can be predicted.

For steady state conditions:

$$\frac{\dot{Q}_s}{A_{du}} = h_{cl}(t_{sk} - t_{cl}) = h_c f_{cl}(t_{cl} - t_a) + h_r f_{cl}(t_{cl} - t_{mrt}) \qquad [5]$$

where

$\frac{\dot{Q}_s}{A_{du}}$ = sensible heat dissipation rate per unit surface area of nude body; kcal/hr·m^2 (Btuh·ft^2)

t_{sk} = weighted mean skin temperature (from Eq [3]; C (F))

t_{cl} = clothing surface temperature; C (F)

t_a = ambient air dry-bulb temperature; C (F)

t_{mrt} = mean radiant temperature; C (F)

h_{cl} = conduction heat transfer coefficient through clothing; kcal/hr·m^2·C (Btuh·ft^2·F)

h_c = convection heat transfer coefficient; kcal/hr·m²·C (Btuh·ft²·F)

h_r = linear radiation heat transfer coefficient; kcal/hr·m²·C (Btuh·ft²·F)

f_{cl} = ratio of clothed body to nude body surface areas.

Since neither the actual heat transfer rate nor the clothing surface temperature were measured, estimates for these values are necessary. The conduction heat transfer coefficient h_{cl} (11) can be estimated from:

$$h_{cl} = \frac{1}{0.18\ I_{cl}}, \qquad [6]$$

where h_{cl} is in kcal/hr·m²·C, or,

$$h_{cl} = \frac{1}{0.88\ I_{cl}} \qquad [6a]$$

where h_{cl} is in Btuh·ft²·F .

All tests were conducted with the Standard KSU Uniform which has a measured clo value of I_{cl} = 0.60 as determined by the technique reported by Seppanen, et al. (12); therefore:

$$h_{cl} = 9.25 \text{ kcal/hr·m}^2\text{·C}; \quad (1.89 \text{ Btuh·ft}^2\text{·F})$$

The convection heat transfer coefficients, h_c, for this series of tests were estimated from Eq 4:

Velocity		h_c	
ft/min	m/s	Btuh ft² F	kcal/hr m² C
40	0.2	0.95	4.65
80	0.4	1.34	6.58
160	0.8	1.90	9.30

The linear radiation heat transfer coefficient, h_r, was assumed constant at 4.51 kcal/hr·m²·C (0.92 Btuh·ft²·F) as it only varies ±10% as the MRT deviates ±30 F from a skin temperature of 92.5 F (13).

Therefore, by rearranging Eq 5 and assuming $t_{mrt} = t_a$ for these tests, values for t_{cl} can be calculated for various air temperatures and velocities:

$$t_{cl} = \frac{t_{sk} + \frac{f_{cl}}{h_{cl}}(h_r + h_c)\ t_a}{1 + \frac{f_{cl}}{h_{cl}}(h_r + h_c)} \qquad [7]$$

Sensible heat dissipation rates and clothing surface temperatures, estimated from Eq 5 and 7, are shown in Table 3 for the various values of air temperature and air motion evaluated in this study. Also shown are the corresponding weighted mean skin temperatures, and responses of thermal sensation and air motion affectivity measured after three hours of exposure.

Analysis of these data showed that linear relationship existed between the weighted mean skin temperatures and thermal sensations and between calculated sensible heat transfer rates and thermal sensations:

Table 3. CALCULATED VALUES OF HEAT TRANSFER AND CLOTHING SURFACE TEMPERATURES FOR VARIOUS AMBIENT AIR TEMPERATURES AND VELOCITIES. CORRESPONDING VALUES OF WEIGHTED MEAN SKIN TEMPERATURES, THERMAL SENSATIONS, AND AIR MOTION AFFECTIVITIES ARE ALSO SHOWN.

	Ambient Air Temperature	(F)	72.0			78.6			85.2		
		(C)	22.2			25.6			29.5		
	Air Velocity	(ft/min)	40	80	160	40	80	160	40	80	160
		(m/s)	0.2	0.4	0.8	0.2	0.4	0.8	0.2	0.4	0.8
Measured Values	Weighted Mean Skin Temperature*	(F)	90.3	88.0	87.4	93.0	90.8	91.0	94.2	93.3	93.7
		(C)	32.4	31.1	30.8	33.9	32.7	32.8	34.6	34.1	34.3
	Thermal Sensation*		3.0	1.9	2.7	4.3	3.7	3.4	4.7	4.6	4.5
	Air Motion Affectivity*		5.3	4.2	4.2	5.0	5.0	4.8	4.0	4.7	4.4
Calculated Values	Clothing Surface Temperature	(F)	80.7	78.8	77.8	85.5	83.9	83.3	89.5	88.6	88.3
		(C)	27.1	26.0	25.4	29.7	28.8	28.5	32.0	21.4	31.3
	Sensible Heat Loss Rate	(Btuh ft^2)	18.0	17.1	18.1	14.2	13.1	14.6	8.9	8.5	9.9
		(kcal/h m^2)	49.0	46.6	49.3	38.7	35.7	39.8	24.2	23.1	27.0
	Standard ET* or T_{SO} at 50% RH	(F)	69.8	69.2	67.2	76.5	76.0	73.9	84.0	83.7	82.4
		(C)	21.0	20.7	19.5	24.7	24.4	23.3	28.9	28.7	28.0

*For males and females combined after 3-hour exposure.

$$Y_{TS} = 0.377\, t_{sk} - 20.75 \quad ; \quad t_{sk} = F$$

$$Y_{TS} = 0.675\, t_{sk} - 18.59 \quad ; \quad t_{sk} = C \qquad [8]$$

$$r = 0.95$$

$$S_{Y \cdot X} = 0.28$$

Y_{TS} = thermal sensation

t_{sk} = weighted mean skin temperature

and

$$Y_{TS} = 6.72 - 0.083\left(\frac{\dot{Q}_s}{A_{du}}\right) \quad ; \quad \frac{\dot{Q}_s}{A_{du}} = \frac{kcal}{hr \cdot m^2}$$

$$Y_{TS} = 6.72 - 0.226\left(\frac{\dot{Q}_s}{A_{du}}\right) \quad ; \quad \frac{\dot{Q}_s}{A_{du}} = \frac{Btu}{hr \cdot ft^2} \qquad [9]$$

$$r = -0.88$$

$$S_{Y \cdot X} \quad 0.44$$

$\frac{\dot{Q}_s}{A_{du}}$ = sensible heat transfer rate .

These data are shown graphically in Fig. 6 and 7. Comparative data points were determined from the model of Gagge et al. (10) using skin temperatures and sensible heat transfer rates corresponding to the "preferred" temperatures shown in Table 2. The thermal sensation was determined from Eq 2 using the "preferred" temperature (at 50%) and the appropriate velocity.

Because linear relationships were not detected between t_{sk} or $\frac{\dot{Q}_s}{A_{du}}$ and air motion affectivity, parabolic curves were determined by the method of least squares; these are presented in Figs. 8 and 9, and described as follows:

$$Y_{Am} = 15.3217\ t_{sk} - 0.0843\ t_{sk}^2 = 691.34 \quad ; \quad t_{sk} = F$$
$$Y_{Am} = 17.7997\ t_{sk} - 0.2718\ t_{sk}^2 - 286.29 \quad ; \quad t_{sk} = C \qquad [10]$$

and

$$Y_{Am} = 1.46 + 0.1760\left(\frac{\dot{Q}_s}{A_{du}}\right) - 0.0023\left(\frac{\dot{Q}_s}{A_{du}}\right)^2 \quad ; \quad \frac{\dot{Q}_s}{A_{du}} = \frac{kcal}{hr\cdot m^2}$$
$$Y_{Am} = 1.54 + 0.4668\left(\frac{\dot{Q}_s}{A_{du}}\right) - 0.0165\left(\frac{\dot{Q}_s}{A_{du}}\right)^2 \quad ; \quad \frac{\dot{Q}_s}{A_{du}} = \frac{Btu}{hr\cdot ft^2} \qquad [11]$$

where Y_{Am} = air motion affectivity.

Examination of Figs. 6 to 9 indicates that an interesting relationship apparently exists between the thermal sensation and air motion affectivity. From Fig. 6, a comfort vote of 4.0 would be predicted for a weighted mean skin temperature of 92.4 F, while a vote of slightly pleasant (5.2) would be predicted from Fig. 8, for this same skin temperature. In other words, if the skin temperature is 92.4 F, thermal comfort would be reported and the response to the air motion would be slightly pleasant.

Similar responses can also be predicted from the thermal sensation, the rate of sensible heat transfer, and the air motion affectivity (see Fig. 7 and 9). The rate of sensible heat loss at which a subject would probably be thermally comfortable and most pleasantly affected by the air motion is approximately 32 to 35 kcal/hr•m^2. Fanger (14) has indicated that at sedentary conditions (50 kcal/hr•m^2) approximately 15 kcal/hr•m^2 will be dissipated as evaporative loss from respiration and diffusion (no regulatory sweating), resulting in 35 kcal/hr•m^2 dissipated as sensible heat. The two-node model (10) coupled with Eq 2 also indicates that at values of approximate 35 to 40 kcal/hr•m^2 thermal comfort would be predicted at sedentary conditions when there is no metabolic storage.

Recently, Gonzales and Gagge (15) have introduced the Standard Operative Temperature (T_{SO}) or Standard Effective Temperature (SET*) for thermally equivalent environments; this is identical to that used in establishing the ASHRAE ET*, and is expressed as:

$$SET* = \left[\frac{h\ F_{cl}}{h'\ F'_{cl}}\right]t_a + \left[1 - \frac{h\ F_{cl}}{h'F'_{cl}}\right]\ t_{sk} \qquad [12]$$

where $h = h_c + h_r$

F_{cl} = thermal efficiency factor expressed as:

$$F_{cl} = \frac{\frac{h_{cl}}{f_{cl}}}{[\frac{h_{cl}}{f_{cl}} + h]}$$

When the terms F_{cl} and h are calculated from the experimental conditions and the standard conditions (F'_{cl} = 0.58 and h' = 7.0 kcal/hr$\cdot$m$^2\cdot$C) are substituted into Eq 12, the Standard ET* condition can be determined. These are shown in the bottom row of Table 3. Analysis of these data showed that a linear relationship existed between SET* and the thermal sensation Y_{TS}:

$$Y_{TS} = 0.140\ (SET^*) - 6.968\ , ; \quad SET^* = F \tag{15}$$

$$r = 0.923$$

$$S_{Y \cdot X} = 0.35$$

These data are presented graphically in Fig. 10. The "predicted" values were determined by substituting the SET* values into Eq 1 assuming H constant at 50%.

The existence of the high correlations between the thermal sensation and the weighted mean skin temperature (r = 0.95), the thermal sensation and sensible heat transfer from the body surface area (r = -0.88), and between the thermal sensation and SET*(r = 0.92) (Eq 8, 9 and 15) permit the accurate prediction of the thermal sensation from any of these variables for sedentary activity. Two points can be made at this time: (1) if it is possible to identify these optimum values, energy consumption rates could also be optimized while maintaining pleasant and thermally comfortable conditions; and (2) it is not unreasonable to assume that we now possess the techniques required to initiate research on energy optimization and its effects on human response.

SUMMARY AND CONCLUSIONS

Ninety college-age students, 45 men and 45 women, were exposed for 3 hours in groups of 5 to three temperatures (72.0, 78.6, 85.2 F) each at three air velocities (40, 80, 160 ft/min). Weighted mean skin temperatures were determined for each subject in addition to obtaining the affective responses to thermal sensation, air movements, and sound levels.

From the results of this study, it was concluded that:

1) Thermal sensations, air motion and sound level affectivities, and weighted mean skin temperatures all demonstrated significant exposure period adaptations.

2) Similar to still air conditions, no significant sex differences existed in thermal sensations at the higher velocities tested after 3 hours' exposure.

3) Significant differences in temperature and temperature by air motion interaction indicate the importance of convection heat transfer in predicting thermal sensations and air motion affectivity.

4) Significant differences existed between the sound level affectivities of men and women during exposure to the three air movement conditions, and these differences increased with increasing sound level, but not significantly.

5) Weighted mean skin temperatures were significantly influenced by air temperatures and velocities; they also exhibited significant interactions between air motion and exposure period, and temperature and exposure period. Several secondary interactions also existed, indicating that skin temperature should be a sensitive correlate of thermal sensation and air motion affectivity.

6) Thermal sensations may be linearly correlated with the new ASHRAE Effective Temperature and air movement.

7) A linear regression existed between weighted mean skin temperatures and thermal sensations, while a parabolic correlation existed between weighted mean skin temperature and air motion affectivities.

8) Heat loss rates calculated from this study compare favorably to values reported in literature. These values indicate that they also may be linearly correlated with thermal sensation for the conditions of these tests while air motion affectivity may be correlated parabolically.

REFERENCES

1. Rohles, F. H., Wind as an aversive stimulus, J. Exp. Anal. Behav., 8, 203-206, 1965.

2. Rohles, F. H., A psychologist looks at air movement, ASHRAE J., 7 (7), 48-49, 1965.

3. Rohles, F. H., Aversive quality of low velocity winds at various ambient temperatures, Aerospace Med., 21, 896-898, 1970.

4. Rohles, F. H. and R. G. Nevins, The nature of thermal comfort for sedentary man, ASHRAE Trans., 77 (I), 239-246, 1971.

5. Goldman, R. F., Personal communication, 1970.

6. Houghten, F. C. and C. P. Yaglou, Cooling effect on human beings by various air velocites, ASHVE Trans., 30, 193-212, 1924.

7. Morse, R. N. and J. J. Kowalczewski, A rational basis for human thermal comfort, ASHRAE J., 9 (9), 72-77, 1967.

8. Fanger, P. O., Thermal Comfort, Danish Technical Press, Copenhagen, 1970.

9. Olesen, S., P. O. Fanger, and J. J. Bassing, Physiological comfort conditions at sixteen combinations of activity, clothing, air velocity, and ambient temperature, ASHRAE Trans., 78 (II), 1972.

10. Gagge, A. P., J. A. J. Stolwijk, and Y. Nishi, An effective temperature scale based on a simple model of human physiological regulatory response, ASHRAE Trans., 77 (I), 247-262, 1971.

11. Gagge, A. P., A. C. Burton, and H. C. Bazett, A practical system of units for the description of the heat exchange of man with his environment, Science, 94, 428-430, 1941.

12. Seppanen, O., P. E. McNall, O. M. Munson and C. H. Sprague, Thermal insulating values for typical indoor clothing ensembles, ASHRAE Trans., 78 (I), 120-130, 1972.

13. Gagge, A. P., G. M. Rapp, and J. D. Hardy, The effective radiant field and operative temperature necessary for comfort with radiant heating, ASHRAE Trans., 73 (I), I.2.1-9, 1967.

14. Fanger, P. O., Calculation of thermal comfort: Introduction of a basic comfort equation, ASHRAE Trans., 73 (II), III.4.1-20, 1967.

15. Gonzales, R. R., A. P. Gagge, Magnitude estimates of thermal discomfort during transients of humidity and operative temperature and their relation to the new ASHRAE effective temperature (ET*), ASHRAE Trans., 79 (I), 1973.

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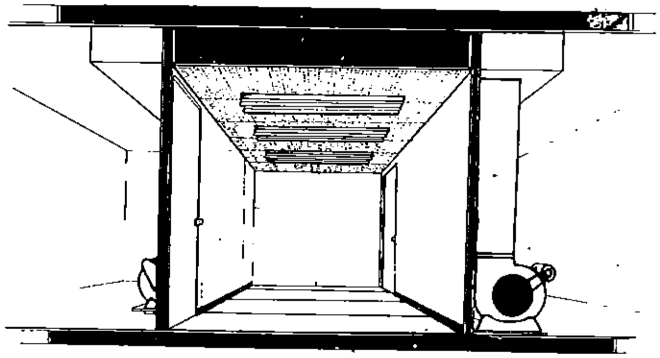

Fig. 1 *The KSU-ASHRAE chamber showing a cutaway view of the test room and air-distribution system*

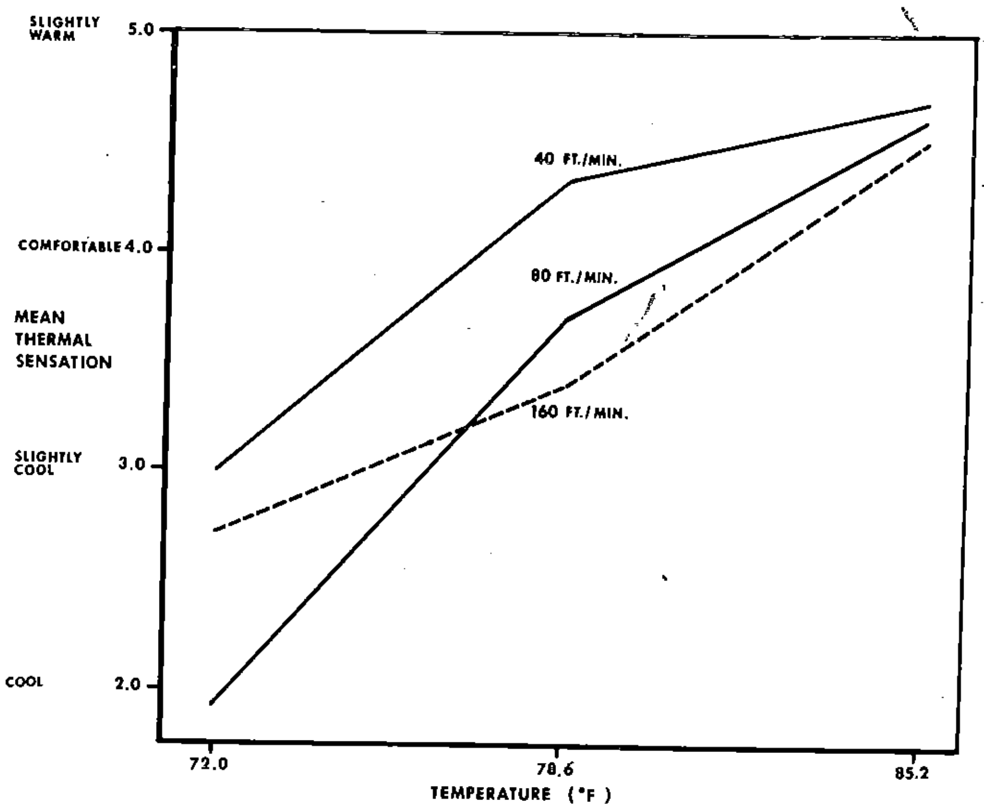

Fig. 2 *Mean thermal sensations for sedentary subjects following a 3-hour exposure to 3 dry-bulb temperatures under 3 air movement levels*

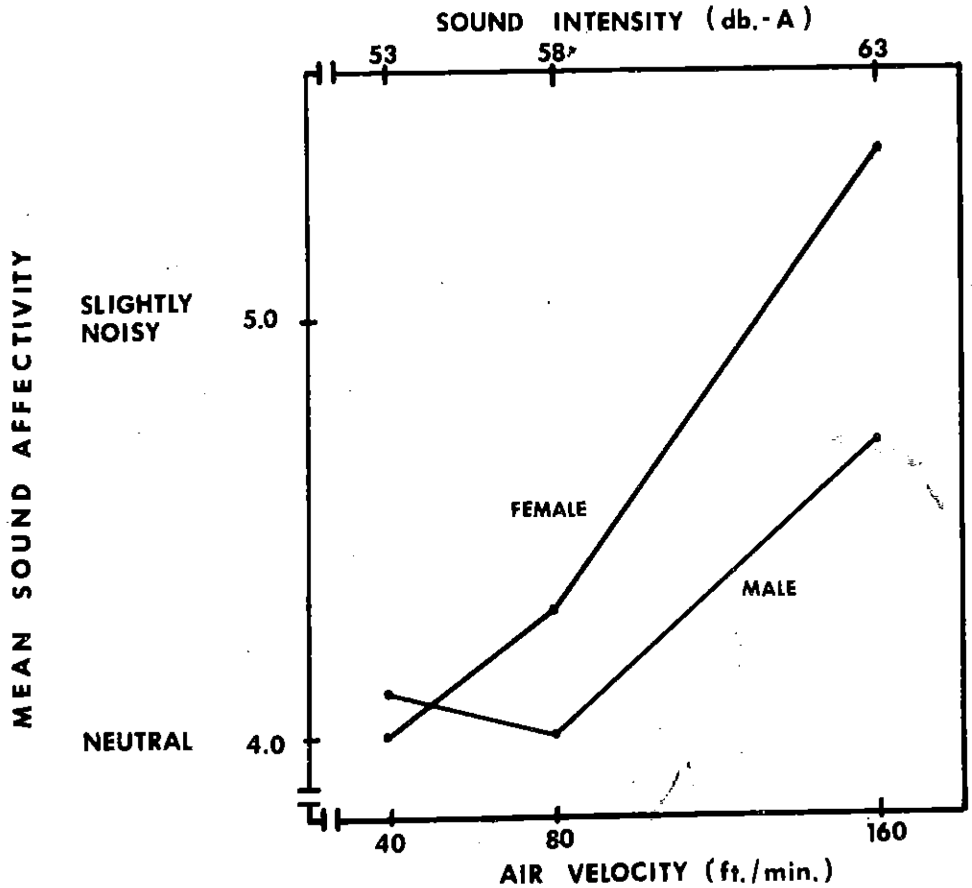

Fig. 3 Mean affective responses of males and females following a 3-hour exposure to 3 sound levels associated with 3 air velocities

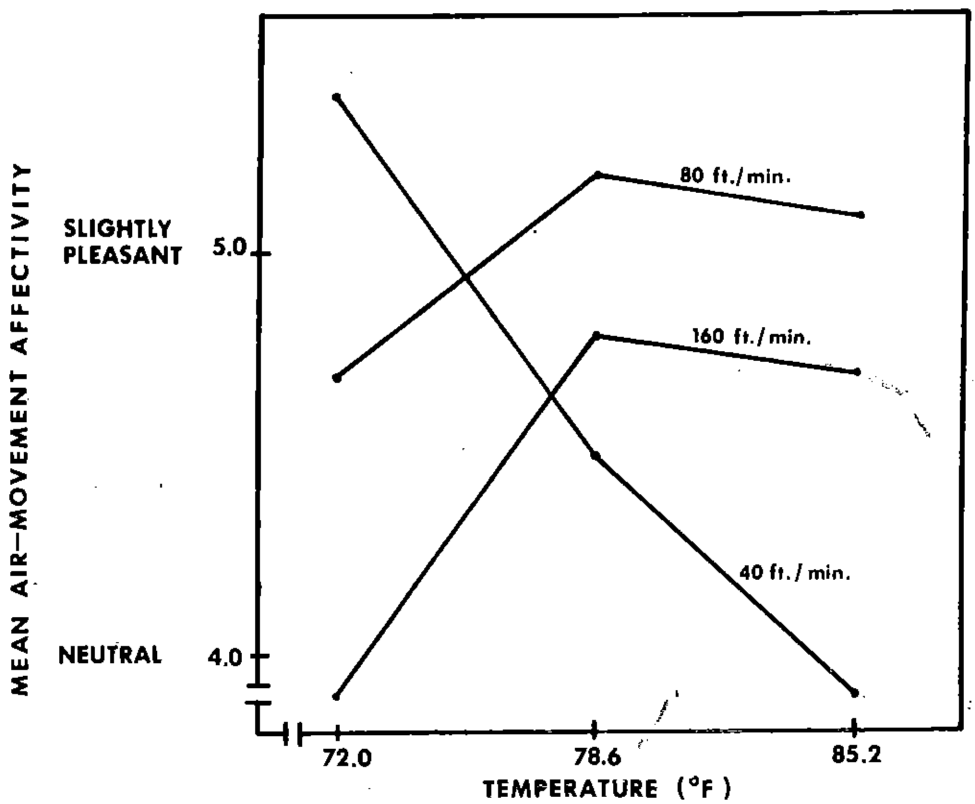

Fig. 4 Mean affective responses of sedentary subjects exposed for 3 hours to 3 air movement levels under 3 temperature conditions

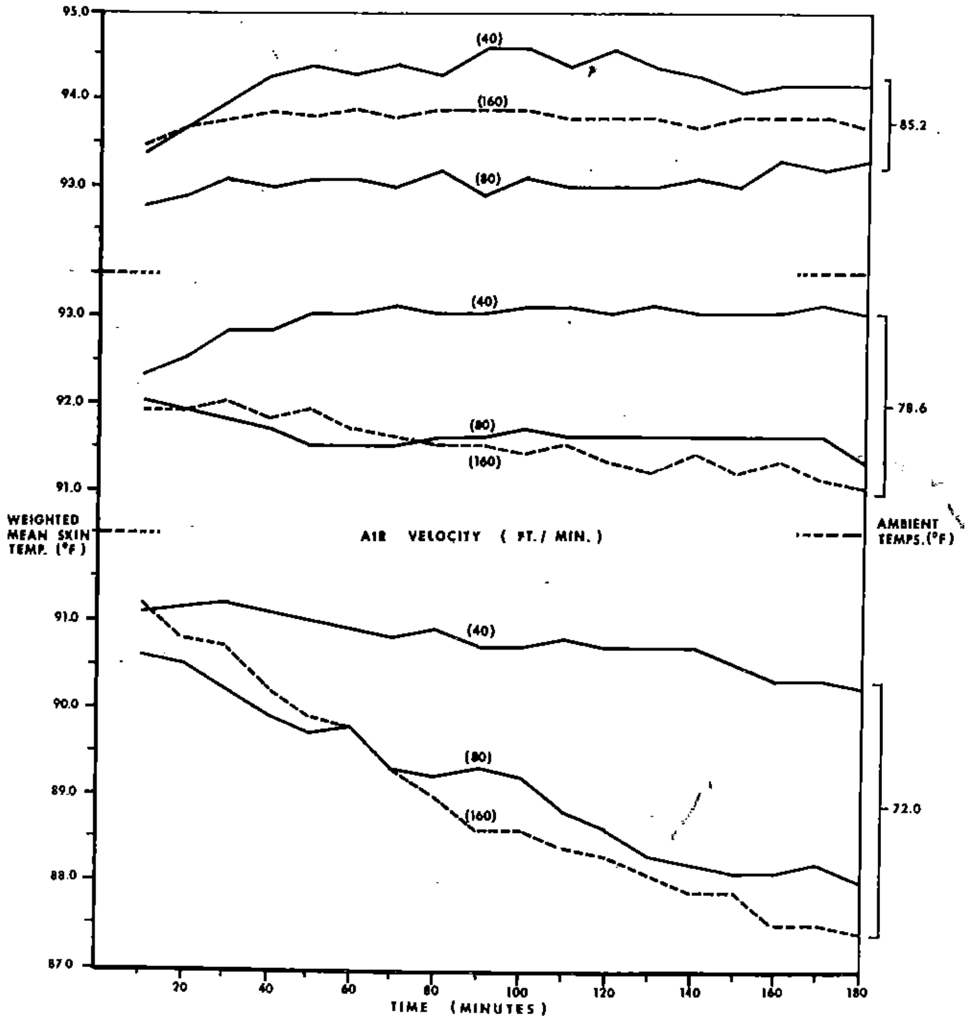

Fig. 5 *Weighted mean skin temperature for sedentary subjects during a 3-hour exposure at 3 air velocities and 3 ambient temperatures*

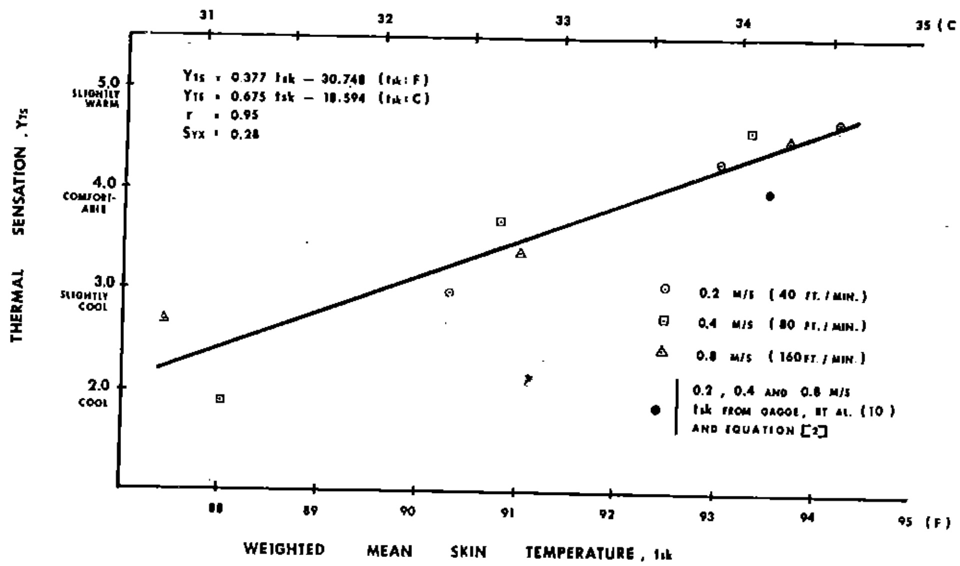

Fig. 6 The relationship between the thermal sensation and the weighted mean skin temperature for sedentary subjects exposed for 3 hours to various air temperatures and velocities

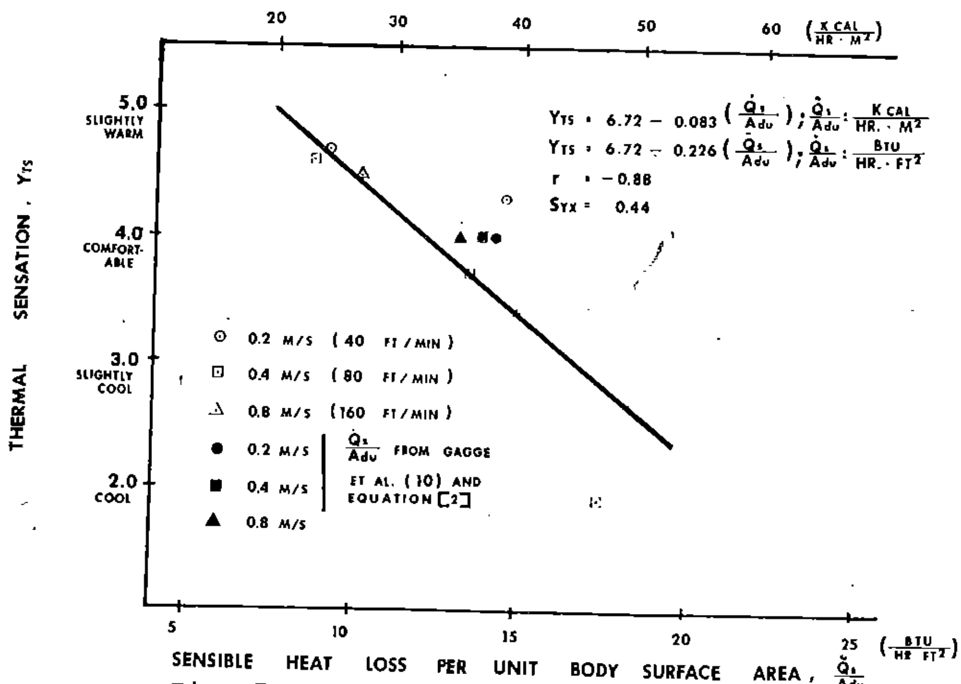

Fig. 7 The relationship between the thermal sensation and the sensible heat loss per unit body surface area for sedentary subjects exposed for 3 hours to various air temperatures and velocities

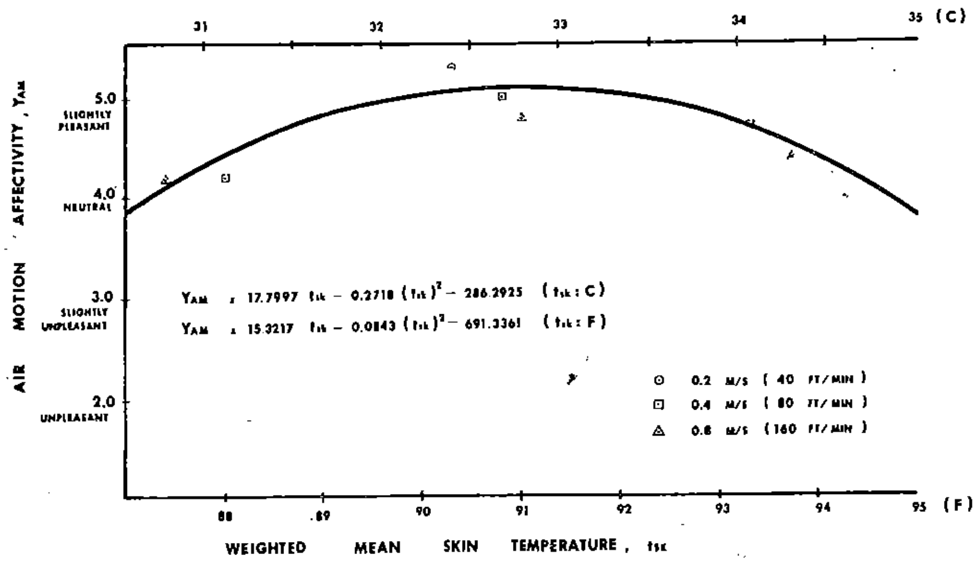

Fig. 8 The relationship between the air motion affectivity and the weighted mean skin temperature for sedentary subjects exposed for 3 hours to various air temperatures and velocities

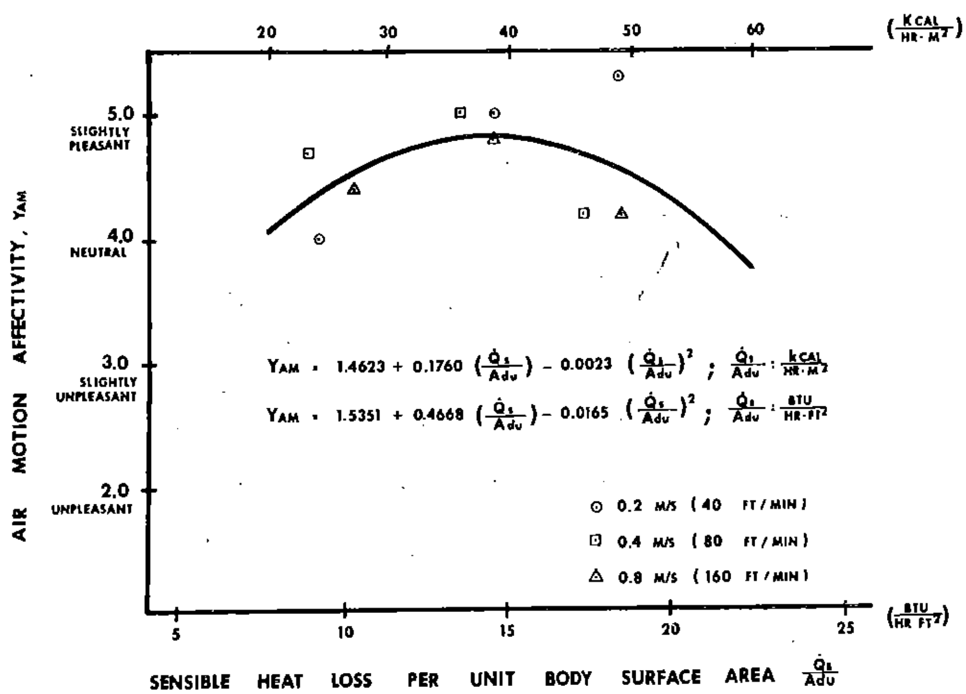

Fig. 9 The relationship between the air motion affectivity and the sensible heat loss per unit body surface area for sedentary subjects exposed for 3 hours to various air temperatures and velocities

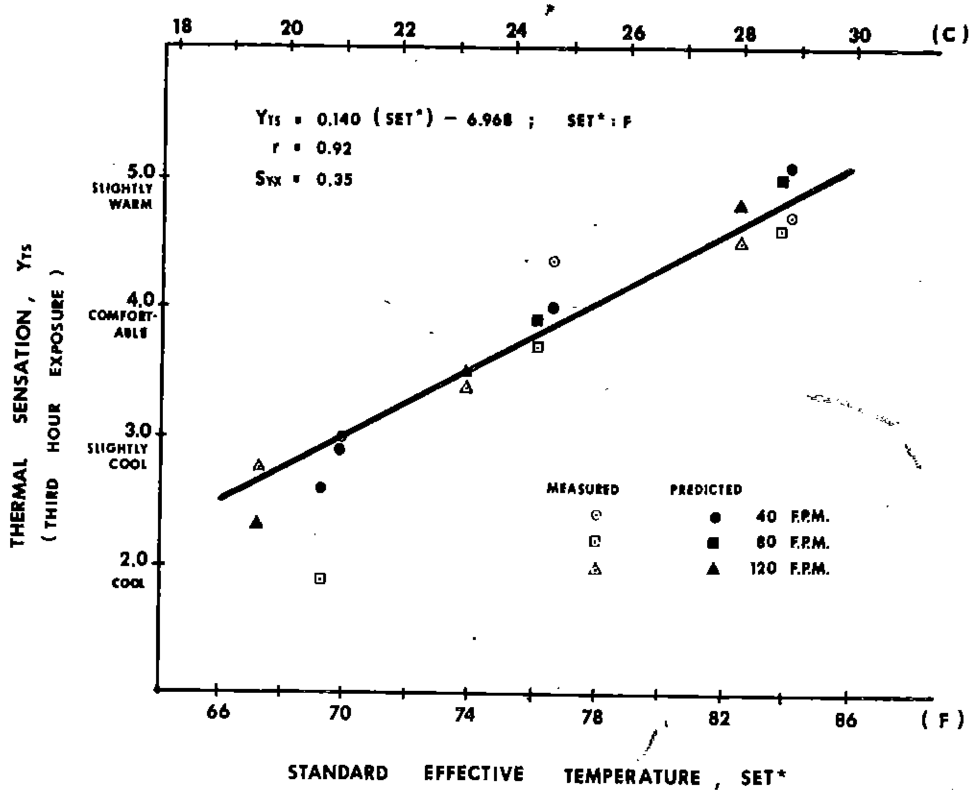

Fig. 10 *The relationship between the thermal sensation and the standard effective temperature for sedentary subjects exposed for 3 hours to various air temperatures and velocities*

DISCUSSION

DAN VANDAMENT (Consulting Engineer, Mill Valley CA): Was consideration given to weight of subjects, i.e, size, mass, also age of subjects, particularly in relation to skin temperature and weight loss?
DR. ROHLES: No special consideration was given to the weight, size, nor age of the subjects.
R.H. PERRINE (U.S. Army, Yuma Proving Ground, Yuma AZ): Why were there no sex differences?
DR. ROHLES: I am at a loss to know why we did not uncover any sex differences. As I mentioned, this is one of the first studies we have conducted in which no sex differences were apparent.
MR. PERRINE: Was the noise effect on hearing considered to be greater on females than on males?
DR. ROHLES: The findings concerning the response to the increased intensity was greater in the females than in the males and is a finding that has been reported by other investigators.
MR. PERRINE: Was skin temperature weighting based on body mass in the pertinent area?
DR. ROHLES: Skin temperature weighting is based on the body mass in the three areas.
JON M. RUECK (Owens-Corning Fiberglas Corp, Toledo OH): In a recent discussion with you in Manhattan, you stated that you planned to use your Eq (3) to construct a table of air velocities that are required at various ambient temperatures to maintain thermal comfort. Have you done that?
DR. ROHLES: Yes, we have, Jon. The table is presented below.

AIR VELOCITIES REQUIRED AT
VARIOUS AMBIENT TEMPERATURES (ET*)
TO MAINTAIN THERMAL COMFORT

ET* (F)	AIR VELOCITY (FT/MIN)
80	48
85	309
90	571
95	833

TO MAINTAIN COMFORT, AN INCREASE IN THE AIR VELOCITY OF 52.4 FT/MIN (0.6 MPH) IS REQUIRED FOR EVERY ONE DEGREE INCREASE IN ET*.