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Thermal and Comfort Sensations of Sedentary Persons Exposed to Asymmetric Radiant Fields

INTRODUCTION

The results of a recent study (1) conducted by the Institute for Environmental Research at Kansas State University determined the relative effects of convection and radiation heat transfer with a uniform radiant field on the thermal sensation of sedentary human subjects. Also reported in that study was a suggested "Thermally Neutral Zone" for sedentary subjects. That zone consists of combinations of air temperature and MRT* that would predictably evoke thermal sensation votes from the maximum number of sedentary subjects between slightly cool and slightly warm (with constant air velocity and partial pressure of water vapor in the air). The results of a more recent study (2) at that laboratory examined the effect of an asymmetric radiant field on the thermal and comfort sensations of sedentary subjects. In that study subjects were exposed to enclosure surfaces with 12 F temperature separations. The results indicated that the previously mentioned "Thermally Neutral Zone" was applicable for exposure to an asymmetric radiant field of the degree investigated, with the subjects experiencing no significant discomfort which could be attributed to the asymmetry. Also it was found that for purposes of MRT calculations seated subjects could be approximated as possessing spherical geometry. The ballots used for determining a subject's thermal and comfort sensations for both studies are shown in Figs. 1 and 2 respectively.

It was the purpose of the present study to extend the results of these previous studies by investigating the thermal and comfort sensations of subjects exposed to more severe degrees of asymmetric radiant fields. The asymmetries investigated are felt to be as severe as those usually encountered in well designed building systems in the field.

The MRT's reported in the tests were evaluated with a Honeywell two-sphere radiometer (4). Based on the results of a previous study (2), it is felt that the Honeywell radiometer, with its spherical sensor, indicates with sufficient accuracy the MRT of seated subjects.

FACILITIES

This research program was conducted in the KSU-ASHRAE laboratory facility of the Institute for Environmental Research located on the campus of Kansas State University. The environmental test chamber is 12 ft by 24 ft in plan and an 8 ft ceiling

*The temperature of a uniform black enclosure in which an occupant would exchange the same amount of radiant heat as in the existing non-uniform environment, from ASHRAE Standard 55-66, Thermal Comfort Standard.

SUBJECT

NAME______________________________NO.________

Circle the number that describes how you feel:

1. Cold
2. Cool
3. Slightly Cool
4. Neutral
5. Slightly Warm
6. Warm
7. Hot

____

____

Fig. 1. The Ballot Used to Evaluate the Thermal Sensation Response of the Subjects

SUBJECT

NAME______________________________NO.________

Circle the letter that describes your feeling:

A. Comfortable
B. Slightly Uncomfortable
C. Uncomfortable
D. Very Uncomfortable
E. Intolerable

____

____

Fig. 2. The Comfort Ballot Used to Evaluate the Comfort Sensation Response of the Subjects

height was employed. It has capabilities of excellent control of air temperature, wet bulb temperature, chamber surface temperatures, and air velocity. A complete description of the laboratory facility is included in Nevins, et al (3).

MRT was measured in the test chamber by means of a Honeywell 2-sphere radiometer (4). The radiometer has two spheres, one gold-plated and polished, while the other sphere has a blackened surface. Within each sphere are electric resistance heaters which supply the power necessary to maintain both spheres at a common, thermostatically controlled temperature higher than air temperature. Since the spheres are geometrically identical, operate at the same temperature, and are located in the same environment, the conduction and convection heat losses for the spheres are equal. Hence the difference in heat inputs to the two spheres is equivalent to the difference of their radiation heat losses. The radiometer integrates the difference in sphere heat input during a five minute interval. Knowledge of this heat input difference and the set-point temperature of the two spheres allows for evaluation of the mean radiant temperature, MRT, from convenient operating curves accompanying the radiometer. The average error has been measured as less than .4 F in evaluating MRT (5).

During the environmental tests, the radiometer was placed in the chamber in a position similar to the placement of a typical subject (Figs. A-1 and A-2 Appendix A), with the spheres 2 ft from the floor.

EXPERIMENTAL DESIGN

One of a person's most severe exposure to an asymmetric radiant field occurs when large single-pane glass areas are used. If these are heat-absorbing, special problems may also occur. Where radiant panels are used for space heating or cooling, severe asymmetric conditions may also be present. In such cases the occupants may be exposed to one of four distinct types of asymmetric radiant fields, namely overhead or lateral exposure to heated or cooled panels. Corner situations have not been considered. Four separate test series were conducted to investigate separately the effect of these asymmetric radiant fields on the subject's thermal and comfort sensations.

Cool Wall Series

In this series of tests the long west wall of the test chamber was maintained at a temperature 20 F lower than the balance of the surfaces of the test chamber (walls, ceiling and floor). The experimental combinations of MRT and air temperature investigated are shown in Fig. 3 and Table 1 lists the air and test chamber surface temperatures for each Cool Wall test. Five subjects, facing north, were seated such that their radiation shape factor to the west wall was 0.20, assuming the subjects to be of spherical geometry with centers two feet above floor level. Figure A-1, (Appendix A), shows a plan view of the

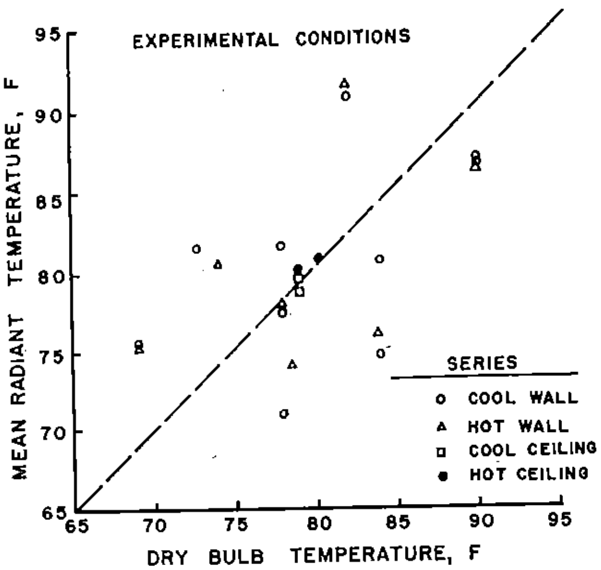

Fig. 3. The Experimental Conditions of MRT and Air Dry Bulb Temperature Investigated

seating arrangement used in this series. The photograph of Fig. 4 pictures a group of subjects during testing.

In all cases reported, the subjects were untrained college-age males and females who volunteered and were paid $5 to participate in one test. They were examined at the Kansas State University Health Service by a physician.

A shape factor of 0.20, with respect to cooled wall, was considered to be comparable to the extreme exposure one would encounter in typical well designed situations. The Honeywell radiometer used to measure MRT was also placed so that its shape factor to the long wall was 0.20. Two replicates of each experimental condition were conducted, resulting in twenty testing sessions with five subjects per session.

Hot Wall Series

The experimental design of the Hot Wall series was essentially the same as that of the Cool Wall series. However, the long west wall of the test chamber was always maintained at 130 F, with the balance of the chamber surfaces chosen such that approximately the same experimental points of the Cool Wall series were obtained. The experimental combinations of MRT and air temperature are shown in Fig. 3 and Table 1 lists the air and chamber surface temperatures for each Hot Wall test. Again two replicates of each experimental condition were conducted resulting in fourteen testing sessions with five subjects per session.

Cool and Hot Ceiling Series

In this series of tests, subjects were exposed to a heated or cooled ceiling. The radiation shape factor for all subjects to the temperature controlled panels of the ceiling was approximately 0.12. Fig. A-2 (Appendix A), shows a plan view of the subject's seating arrangement in the chamber. The experimental conditions for the Cool and Hot Ceiling series are shown in Fig. 3 and the air and chamber surface temperatures for each ceiling test are listed in Table 1. Eight subjects participated in each Cool and Hot Ceiling testing session.

Control Series

In this series, subjects were exposed to an environment of uniform surface temperatures equal to air temperature. 78 F was selected, based on the results of Nevins et al (3), so that a predicted maximum of thermal comfort votes with "neutral" thermal sensations would be obtained. It was felt that the "uniform" thermal environment of the control series would cause minimal subject discomfort for the testing procedure followed. A comparison of the comfort response of subjects exposed to an asymmetric radiant field with the comfort response of the subjects of the control series would expose any significant discomfort which could be attributed to the asymmetry of the radiant field.

Fig. 4. A View of the Test Chamber Showing the Position of the Subjects and Radiometer for the Cool and Hot Wall Series

TABLE 1

EXPERIMENTAL CONDITIONS OF TEST CHAMBER SURFACE TEMPERATURES AND AIR TEMPERATURE INVESTIGATED

COOL WALL SERIES

COND. NO.	AIR TEMP. (F)	CHAMBER SURFACE TEMP. WEST WALL (F)	CHAMBER SURFACE TEMP. BALANCE (F)
1	84	60	80
2	74	66	86
3	90	65	86
4	70	58	78
5	78	56	76
6	82	76	96
7	78	61	81
8	78	48	70
9	84	48	70
10	90	65	85

HOT WALL SERIES

COND. NO.	AIR TEMP. (F)	CHAMBER SURFACE TEMP. WEST WALL (F)	CHAMBER SURFACE TEMP. BALANCE (F)
1	78	130	55
2	84	130	55
3	78	130	62
4	74	130	71
5	90	130	76
6	82	130	85
7	70	130	61

COOL CEILING SERIES

COND. NO.	AIR TEMP. (F)	CHAMBER SURFACE TEMP. CEILING (F)	CHAMBER SURFACE TEMP. BALANCE (F)
1	79	52	80
2	79	51	80

CONTROL SERIES

COND. NO.	AIR TEMP. (F)	CHAMBER SURFACE TEMP. (F)
1	78	78
2	78	78
3	78	78

HOT CEILING SERIES

COND. NO.	AIR TEMP. (F)	CHAMBER SURFACE TEMP. CEILING (F)	CHAMBER SURFACE TEMP. BALANCE (F)
1	79	130	62
2	80	130	61

Water Vapor Partial Pressure: 0.435 in Hg, but reduced when necessary to prevent moisture formation on cooled chamber surfaces.

NOTE: At each test condition approximately equal numbers of males and females participated. For the cool and hot wall series, each condition includes 2 replicates, one with 5 women and one with 5 men. The cool and hot ceiling series employed 4 women and 4 men in a single test for each condition. The control series used 11 subjects for conditions 1 and 2 (due to radiometer placement) 5 women and 6 men in 1 and 6 women and 5 men in 2. Condition 3 used 6 men and 6 women.

The following environmental characteristics of the present study were chosen equal to those of a previous study (1) in order that the comparison of results be of greatest meaning. The partial pressure of water vapor in the test room was generally maintained at 0.435 inches of mercury (45% RH at 78 F, dew point temperature of 55 F). It was felt more important for the purpose of this study to expose subjects to surfaces somewhat cooler than 55 F than strict adherance to a constant water vapor partial pressure. Therefore, where necessary, the water vapor partial pressure was reduced slightly to prevent formation of moisture on cooled chamber surfaces. The findings of Nevins et al (3) show that small changes in air moisture content for the conditions of this study have little effect on a person's thermal sensation, further justifying this decision. Air velocity in the occupied area of the test chamber was approximately 20-30 fpm, the illumination at desk top was 133 foot candles and the noise level was found to be 68 decibels on the c-scale of a General Radio Type 1551-B Sound Level Meter. In so far as possible, these values were held constant throughout all testing.

PROCEDURE

The procedural details of the present environmental tests are essentially identical to those of previous tests (1) (2) conducted by this laboratory to determine the effect of MRT, (both uniform and asymmetric), on the thermal and comfort sensations of sedentary subjects. The subjects, college-age males and females, were clothed in the Kansas State University standard uniforms with a measured insulation value of 0.59 clo. All subjects wore cotton sweat socks, but no shoes. Figure 4 shows a group of subjects during a typical testing session. The physical characteristics of the subjects participating in the testing sessions are shown in Table 2.

All testing sessions were of three hours duration. The thermal sensation ballot was presented individually to each subject immediately after he had taken his seat in the test chamber. After sufficient time for voting, the thermal sensation ballots were collected and approximately three minutes later the subjects were given the comfort sensation ballot. After collecting the comfort sensation ballots the nurse entered the votes on the data sheet. Each pair of thermal and comfort votes thus collected from each subject was considered to be one single vote describing the subject's thermal and comfort sensations at the time of voting. The same procedure was repeated at thirty minute intervals thereafter, resulting in seven votes per subject, each indicating the thermal and comfort sensation of the subject at the time of voting.

RESULTS

Each vote of thermal comfort given by a subject consisted of an evaluation of his thermal sensation and his comfort sensation at the time of voting. Fig. 5 shows the percentage of thermal comfort votes with a comfort sensation response of A, "comfortable," for thermal sensation responses of 3 through 5 ("slightly cool" through "slightly warm") for the various series conducted. The extremes of the thermal sensation scale were truncated because of the relatively small number of votes of thermal sensation for these responses. Fig. 5 illustrates that subjects feeling "slightly cool" tend to have a higher probability of feeling "comfortable" than those feeling "slightly warm" in similar surrounds. It is also apparent from Fig. 5 that the subjects participating in the Hot Wall series appear to have a generally lower probability of feeling comfortable than the subjects of the other series investigated.

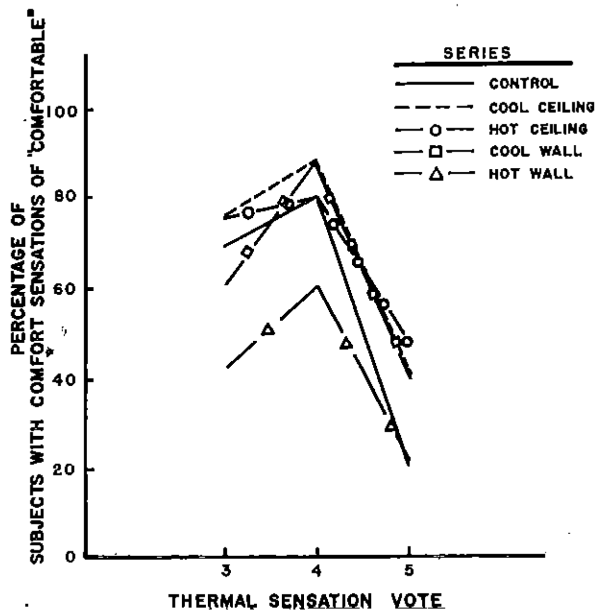

Fig. 5. The Distribution of Comfort Sensation Votes of "Comfortable" within the Thermal Sensation Votes for Sedentary Subjects of All Series Conducted

TABLE 2

PHYSICAL CHARACTERISTICS OF SUBJECTS
PARTICIPATING IN THE COOL AND HOT WALL SERIES

SEX	NO. OF SUBJECTS	AGE (YR)	HEIGHT (IN)	WEIGHT (LB) (NUDE)	SURFACE AREA (FT^2) (NUDE)
Male	85	19.9* ± 1.8**	69.6 ± 2.2	161.8 ± 17.5	20.4 ± 1.3
Female	85	19.8 ± 1.8	64.5 ± 7.6	132.5 ± 17.8	17.7 ± 1.4

*Mean

**Standard deviation

TABLE 3

COMFORT SENSATION RESPONSE OF THERMALLY "NEUTRAL" SUBJECTS

Series	COMFORTABLE		NOT COMFORTABLE (B, C, D, OR E)		TOTAL VOTES
	NO. OF VOTES	%	NO. OF VOTES	%	
Control	89	79.5	23	20.5	112
Cool Wall†	135	87.1	20	12.9	155
Hot Wall†	47	59.5	32	40.5	79
Cool Ceiling	44	88.0	6	12.0	50
Hot Ceiling	52	78.8	14	21.2	66
Series	**CHI-SQUARE VALUES†† CONTROL SERIES**				
Cool Wall†	2.306				
Hot Wall†	8.059***				
Cool Ceiling	1.178				
Hot Ceiling	0.077				

† Based on first four votes
†† Corrected for continuity
*$p < .10$ } no Chi-Square values of these probabilities occurred
**$p < .05$ }
***$p < .01$

For the analysis of the comfort response of subjects exposed to the various degrees of asymmetric radiant field, only the comfort responses accompanied by a thermal sensation response of "neutral" were considered. This was done to eliminate discomfort due to general thermal discomfort which, if not considered, would distort the effect of an asymmetric field on one's general impression of comfort. The votes meeting this criteria were then classified as either "comfortable" (Vote of A on the comfort ballot) or "not comfortable" (Vote of B, C, D, or E). This classification was performed on the votes of the four asymmetric radiant field series and on the Control series. A chi-square test was then performed to determine if the thermally "neutral" subjects of any of the asymmetric radiant field series had a significantly lower probability of feeling "comfortable" than did the thermally "neutral" subjects participating in the Control series. It was felt that any significant difference could be attributed to the asymmetry of the radiation, since the testing procedure was identical for all test series. Table 3 summarizes the results which indicate that, at the 1% probability level, only the subjects of the Hot Wall series had a significantly lower probability of feeling "comfortable" than those of the Control series.

A slightly modified comfort ballot, Fig. 6, was employed during the final three votes of each testing session of the Hot Wall series. By the use of this ballot it was hoped to expose the cause of any discomfort which the subjects observed. Of the thermally "neutral" subjects of the Hot Wall series 75% indicated that the sole, or at least a contributing cause of their discomfort was due to "uneven body temperature" (response 3 of the modified comfort ballot). This result adds further support to the results of the chi-square analysis, indicating that it was indeed the asymmetry of the radiation which caused the subjects of the Hot Wall series to have a significantly lower probability of feeling "comfortable" than the subjects of the Control series.

It was found that the subjects of the Hot Wall series tended to have a lower probability of feeling "comfortable" when the modified comfort ballot Fig. (6) was used than when the standard comfort ballot was used. It was felt that the modified comfort ballot, undoubtedly increased the probability of

NAME____________________________________ NO.______

Circle the letter that describes your feeling:

A. Comfortable

B. Slightly Uncomfortable

C. Uncomfortable

D. Very Uncomfortable

E. Intolerable

If you did not vote A circle the reasons that cause your discomfort:

1. The room is too cool.
2. The room temperature is changing.
3. One side of my body feels warmer than the other (or cooler).
4. The room is too warm.
5. Other (explain)______________________________

____

____

Fig. 6. The Modified Comfort Ballot Used to Determine the Cause of any Subject Discomfort, Used in the "Hot Wall Series"

a subject feeling not comfortable by suggesting causes of discomfort which might otherwise have been ignored. For this reason only the first four votes of thermal comfort, which did not employ the modified comfort ballot, were used in the analysis of comfort sensations for the Hot Wall series. Only the first four votes of thermal comfort were considered in the comfort sensation analysis of the Cool Wall series so that the number of thermally "neutral" votes would more nearly equal the number obtained in the Control series, which employed only the first four votes so as not to affect the last three thermal sensation votes during the control.

A second major purpose of the present study was to determine if the "Thermally Neutral Zone" suggested in the previous paper (1) is applicable for subjects exposed to more severe conditions of radiation asymmetry. This zone was determined from the response of thermal sensations of sedentary subjects exposed to a uniform radiant field, hereafter referred to as the Uniform MRT series.

In order to determine if the "Thermally Neutral Zone" was applicable for the subjects of the Cool and Hot Wall series the following analyses were performed. A multiple regression analysis was conducted on the mean of the final three thermal sensation votes of each subject for the Cool Wall, Hot Wall, and Uniform MRT series. The regression equations based on the votes of males and females combined are listed below. Table 4 summarizes the regression equations for males and females separately, as well as listing the associated supportive statistics.

<u>Uniform MRT Series</u> (1)

$$Y_{m+f} = 4.00 + 0.111\,(t_a - 78.88) + 0.077\,(t_{mrt} - 81.01)$$

$N = 180$

where:

Y_{m+f} = estimated thermal sensation vote of college-age males and females for a given combination of air temperature and MRT

t_a = the independent variable representing air dry bulb temperature, F

t_{mrt} = the independent variable representing MRT (measured by the Honeywell radiometer), F

N = number of subjects

<u>Cool Wall Series</u> (2)

$$Y_{m+f} = 3.97 + 0.121\,(t_a - 80.69) + 0.056\,(t_{mrt} - 80.77)$$

$N = 100$

<u>Hot Wall Series</u> (3)

$$Y_{m+f} = 4.49 + 0.124\,(t_a - 79.53) + 0.035\,(t_{mrt} - 79.94)$$

$N = 70$

Fig. 7 shows lines representing predicted thermal sensations of 4, ("neutral") for the different test series superimposed on the "Thermally Neutral Zone" proposed by McNall, *et al.* (1). The results are based on the regression equations developed for males and females combined.

The regression equations of Table 4 indicate that:

1. The mean thermal sensation for the subjects participating in the Hot Wall series was approximately one-half vote higher than that of the subjects participating in the Uniform MRT

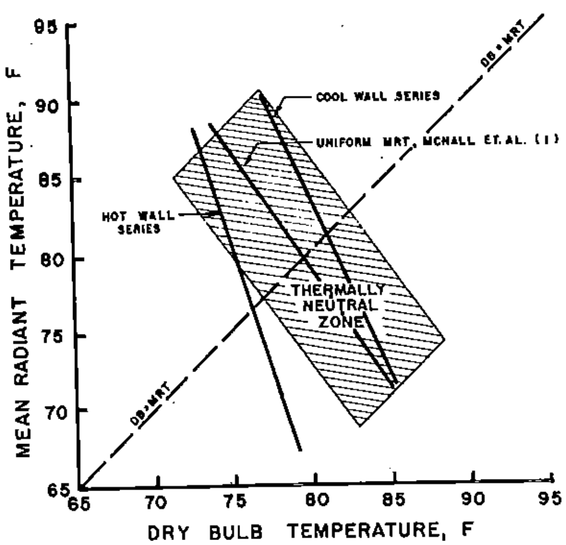

Fig. 7. Lines of Predicted Thermal "Neutrality" for the Males and Females of the Cool and Hot Wall Series and the Uniform MRT Series

series, although the mean of the air temperatures and MRT's were nearly equal for both series.

2. The thermal responses of females participating in the Hot Wall series were apparently insensitive to changes of MRT for the range of MRT investigated. Similarly the thermal sensations of males and females combined of the Hot Wall series were independent of changes of MRT at the 5% probability level. However the coefficient associated with MRT was considered in the construction of the thermally "neutral" line of Fig. 7 since it was felt further testing would expose a significant effect of MRT on thermal sensation.

3. The thermal sensation of females was more dependent on air temperature than was the males'. With the exception of the Hot Wall series, females' thermal sensation was also more highly dependent on MRT than was the males'.

4. The regression equations derived for the Cool Wall series and the Hot Wall series were less efficient than that of the Uniform MRT in predicting thermal sensations. This is evidenced by the generally lower correlations coefficients and higher standard error of estimate associated with the former equations relative to the latter equations.

The resultant regression equations for the Cool Wall and Hot Wall series were separately compared to the regression equation developed for the Uniform

TABLE 4

REGRESSION EQUATION VALUES USED IN PREDICTING THE THERMAL SENSATION OF SEDENTARY SUBJECTS AND SUPPORTIVE STATISTICS

MODEL: $Y = \bar{Y} + b_1 (t_a - \bar{t}_a) + b_2 (t_{mrt} - \bar{t}_{mrt})$

SERIES	SEX	EQ.	$\bar{Y}$	$\bar{t}_a$	$\bar{t}_{mrt}$	b_1	t_{b_1}	s_{b_1}	b_2	t_{b_2}	s_{b_2}	R^2	$s_{y.t_a, t_{mrt}}$	b_1/b_2	NO. OF SUB.
Uniform MRT	M+F	1	4.00	78.88	81.01	0.111	14.65***	0.009	0.077	8.75***	0.009	0.643	0.712	1.43	106
	M		4.03	78.88	81.01	0.099	8.16***	0.012	0.066	5.67***	0.012	0.629	0.651	1.51	80
	F		3.99	78.88	81.01	0.122	8.61***	0.014	0.088	6.53***	0.014	0.688	0.761	1.37	80
Cool Wall	M+F	2	3.97	80.69	80.77	0.121	8.87***	0.014	0.056	3.73***	0.015	0.637	0.747	2.16	100
	M		3.90	80.77	80.83	0.076	4.90***	0.015	0.040	2.34*	0.017	0.541	0.588	2.11	50
	F		4.03	80.61	80.70	0.165	8.72***	0.019	0.072	3.44**	0.021	0.773	0.739	2.32	50
Hot Wall	M+F	3	4.49	79.53	79.94	0.124	6.36***	0.020	0.035	1.68	0.021	0.521	0.857	—	70
	M		4.44	79.49	79.97	0.054	2.21*	0.024	0.058	2.39*	0.024	0.398	0.764	0.93	35
	F		4.54	79.57	79.90	0.194	7.49***	0.026	0.009	0.29	0.030	0.715	0.800	—	35

R^2 = Square of the Multiple Linear Correlation Coefficient

s_{b_i} = Standard Error of b_i

t_{b_i} = t Ratio = $\frac{b_i}{s_{b_i}}$

$s_{y.t_a, t_{mrt}}$ = Standard Error of Y for Given Values

Y = Thermal Sensation, ($\bar{Y}$ = mean Y)

t_a = Air Dry Bulb Temperature, ($\bar{t}_a$ = mean t_a)

t_{mrt} = Mean Radiant Temperature, ($\bar{t}_{mrt}$ = mean t_{mrt})

* = Significant at the 5% Probability Level

** = Significant at the 1% Probability Level

*** = Significant at the 0.1% Probability Level

TABLE 5

COMPUTED F RATIOS IN TESTING THE EQUALITY OF THERMAL SENSATION REGRESSION PLANES

H_o (The two regression planes are equal) vs. H_a (planes not Equal)

REGRESSION EQUATIONS TESTED FOR EQUALITY	SEX	F	DECISION
Uniform MRT and Cool Wall	M+F	2.47	Accept H_o
	M	3.68**	Reject H_o
	F	1.56	Accept H_o
Uniform MRT and Hot Wall	M+F	8.00***	Reject H_o
	M	4.61***	Reject H_o
	F	6.83***	Reject H_o

* = Significant at the 5% probability level – (none occurred)
** = Significant at the 1% probability level
*** = Significant at the 0.5% probability level

MRT series, the basis of the "Thermally Neutral Zone," to determine if the differences were real or could be accounted for by the random variation associated with one's subjective evaluation of thermal sensation. To test the equality between sets of coefficients in two linear regressions, the sum of squares of residuals assuming the equality, and the sum of squares without assuming the equality, are computed. The ratio of the difference between these two sums to the latter sum, adjusted for the corresponding degrees of freedom is distributed as the F ratio under the null hypothesis, i.e. both sets of coefficients equal. The computed F's and decisions regarding the null hypothesis are shown in Table 5. The results of Table 5 show that using the 5% significance level, only the regression equation developed for males and females, and females alone for the Cool Wall series are not significantly different from the corresponding equations applicable for the Uniform MRT series.

DISCUSSION

For a thermal environment to be satisfactory, from a comfort standpoint, it must satisfy both the thermal and comfort sensations of its occupants. Providing thermal "neutrality" is, in itself, not sufficient for thermal comfort. The air movement, air moisture content, etc., may be of such magnitude that, as a result, even the thermally "neutral" individual may experience significant thermal discomfort. Where radiant panels are used, it is possible that the localized heating or cooling experienced by a person, due to the asymmetric radiation, may be sufficient to cause noticeable thermal discomfort.

The results of Table 3 indicate that the subjects participating in the Cool Wall series did not display a significantly different probability of feeling "comfortable" than that of the subjects of the Control series. It can therefore be concluded that although not all of the thermally "neutral" subjects of the Cool Wall series felt "comfortable", the cause of their discomfort could not be attributed to the asymmetry of the radiation. The temperature separation of the long west wall and balance of the test chamber surfaces was 20 F for all Cool Wall test sessions, with the minimum temperature of the west wall being 48 F. The radiation shape factor by which each of the subjects was exposed to the cool west wall was 0.20, assuming the subjects to be of spherical geometry. It can be assumed that for less severe exposure to lateral cooled panels the asymmetry of the radiant field would not have a deleterious effect on one's evaluation of comfort sensation.

The Cool Ceiling series was undertaken to determine if the presence of overhead cooling panels would cause discomfort. It was felt that, although only a 0.12 radiation configuration factor for subject to cooling panel was used, discomfort might be experienced due to the exposure of the surfaces of the face and forehead to the cool ceiling. Such was not the case, however. The average temperature of the ceiling was 51.5 F for the two Cool Ceiling tests.

The results of the Cool Wall and Cool Ceiling indicate that exposure of persons with radiation shape factors of 0.20 and 0.12 to 50 F lateral and overhead panels, respectively, should not cause discomfort due to the asymmetry of the radiant field. 50 F is felt to be the lowest practical temperature the environmental engineer should encounter in well designed situations.

The subjects in the Hot Ceiling series indicated they felt no noticeable discomfort which could be attributed to the presence of a 130 F ceiling. Again, a 0.12 radiation shape factor, subject to ceiling, was used. This result is somewhat in contradiction with that of Chrenko (6). Chrenko correlated frequency of "unpleasantness" with EMRT, (elevated MRT). EMRT was defined as the elevation in MRT at head level, due to the presence of a heated panel, assuming all other enclosure surfaces were of uniform temperature. Chrenko (6) suggests, based on his tests, that the EMRT should not exceed 4 F where the length of exposure is greater than 30 minutes. The calculated average EMRT of the Hot Ceiling series was found to be 10 F. It is felt that the criteria proposed by Chrenko is somewhat conservative for the following reason. There was no attempt by Chrenko to offset the EMRT by a corresponding reduction in air temperature in order to maintain uniform thermal sensations. From Fig. 5 it is obvious that the probability of feeling "comfortable" varies considerably with a person's thermal sensation. Therefore, it is felt that overall thermal effects should be constant if comfort is to be evaluated for various levels of asymmetric radiation. In the present study, this was accomplished by considering only the comfort sensations of subjects who were thermally "neutral" at the time of voting. Although Chrenko (6) reports that the primary cause of his subjects' discomfort was not due to "general thermal discomfort", it is difficult to understand how discomfort for that reason was avoided.

The results of the analysis of the comfort responses of the subjects of the Hot Wall series indicated that that degree of radiation asymmetry had an adverse effect on the subject's relative evaluation of comfort. In all Hot Wall testing sessions the long west wall of the test chamber was maintained at 130 F, while the balance of the test chamber surface temperature varied in the different testing sessions from 55 – 85 F. Based on the above results it follows that thermal environments of this degree of asymmetry should be avoided.

Because of the apparent equality of the regression planes developed from the votes of thermal sensations of the subjects of the Cool Wall series and the Uniform MRT series, the "Thermally Neutral Zone", Fig. 7, proposed by McNall *et al.* (1), is suggested as applicable for persons exposed with radiation shape factors of 0.20 to cool walls as low as 50 F.

The regression analysis of the thermal sensations of subjects of the Hot Wall series produced some unexpected results. The resulting regression planes for males and females combined, males alone, and females alone were all found to be significantly different from the corresponding planes of the Uniform MRT series. As illustrated in Fig. 7 the combinations of MRT and air temperature which would predictably elicit thermal sensations of "neutral" for the Hot Wall series are seen to be significantly lower than for the Uniform MRT series. In fact a major portion of the thermally "neutral" line for the Hot Wall series lies outside the "Thermally Neutral Zone" proposed by McNall *et al.* (1). The thermal sensations of the subjects of the Hot Wall series were apparently biased by the presence of the heated wall. That is, the localized sensation of "warmth" radiated by the heated wall apparently caused the subjects to feel "warmer" than if they were subjected to an equivalent, but less asymmetric radiant field, as measured by the radiometer.

It is interesting to compare the average calculated heat losses for subjects at thermally "neutral" conditions with their average metabolic rates. The average metabolic rate of the sedentary subjects was predicted from the results of McNall *et al.* (7). Since the metabolic rates of males and females are different, each sex was considered separately. The regression equation reported by Fanger (8) was used to determine the average skin temperature, $\bar{t}_s$, for thermally "neutral" subjects. The value of MRT equal to air temperature that would predictably elicit thermal responses of "neutral" was determined from the appropriate regression equations of Table 4. The average evaporative heat loss of subjects, whose average of vote of thermal sensation during the final hour of testing was between 3.5 and 4.5 was determined from their net weight loss. Appendix B describes the calculations of the radiative and convective heat losses, $R + C_V$, for the average male and female of the Hot Wall series.

From Table 6 it is noted that there is good agreement between the calculated and measured heat losses and the metabolic rates for the subjects of the Cool Wall series. However, for the Hot Wall series the calculated and measured heat losses exceed the predicted metabolic rates by approximately 30% for both the males and females. Figure 8, which shows the mean thermal sensation with exposure time, indicates that the subjects of the Hot Wall series had attained equilibrium in their votes before the third hour. This suggests that the human body reacts physiologically to lower the average skin temperature, reducing $R + C_V$ losses, when exposed to unilateral radiant heating. It would seem the regression equation for average skin temperature reported by Fanger (8) does not hold for thermal environments of this nature. More work is suggested, however, to adequately determine the long-term effects of this biased response of thermal sensation.

The thermal sensations of females of the Hot Wall series were found to be independent of changes

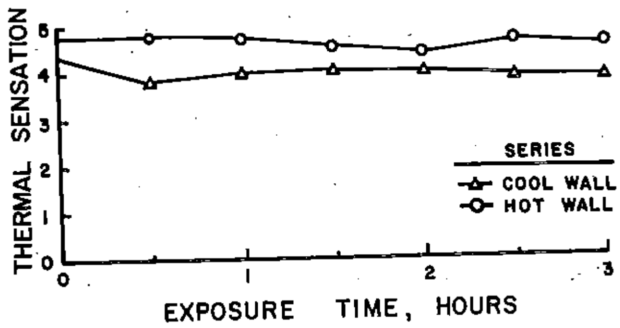

Fig. 8. The Trend of Mean Thermal Sensation Votes with Exposure Time for the Subjects of the Cool and Hot Wall Series*

in MRT, while the males were found to be slightly more sensitive to MRT changes than air temperature changes. The reason for this inconsistency is not understood. For both sexes, the estimated standard deviation of thermal sensations for the Hot Wall series was larger than those found for either the Uniform MRT and Cool Wall series. It is felt that this was due to the localized heating, which caused some confusion in the subject's evaluation of his own thermal sensation.

Because of the obvious difference of the regression planes for the Hot Wall series and the Uniform MRT series, the "Thermally Neutral Zone" proposed by McNall *et al* (1) is not applicable for persons exposed with a radiation shape factor of 0.20 to a panel of 130 F. For less extreme conditions of exposure to heated panels it is assumed the "Thermally Neutral Zone" of McNall *et al.* (1) would be applicable. Some basis for this assumption can be obtained from the responses of thermal sensation of the subjects

TABLE 6

METABOLIC HEAT PRODUCTION COMPARED TO HEAT LOSS FOR THE AVERAGE MALE AND FEMALE WHOSE THIRD HOUR AVERAGE THERMAL SENSATION WAS BETWEEN 3.5 AND 4.5

SERIES	SEX	M (PRED.)	E (MEAS.)	$R + C_V$ (CALC.)	TOTAL (HEAT LOSS)	DIFFERENCE (HEAT LOSS-HEAT PROD.)
		(BTU/HR-FT^2)				%
Cool Wall	Male	19.31	9.11	10.37	19.48	0.9
	Female	17.06	6.55	11.43	17.98	5.4
Hot Wall	Male	19.31	9.77	15.26	25.03	29.7
	Female	17.06	8.15	14.02	22.17	29.9

of the Hot Ceiling series. The predicted mean thermal sensation, based on the regression planes developed for the Hot Wall and Uniform MRT series is 4.42 and 4.05, respectively. The observed mean was 4.00, which suggests that the thermal sensations of persons exposed with a 0.12 radiation shape factor to 130 F panels is more accurately predicted by use of the regression plane developed for Uniform MRT than that for the Hot Wall Series.

SUMMARY AND CONCLUSIONS

The results of the statistical analyses performed on the votes of thermal comfort of sedentary male and female subjects wearing clothing with an insulation value of 0.59 clo in equilibrium with environments with a partial pressure of water vapor of 0.435 inches Hg and air velocity of 20-30 fpm indicate that:

1. The thermal sensations of subjects exposed with radiation shape factors of 0.20 to a wall 20 F cooler than the balance of enclosure surfaces and the thermal sensations of subjects exposed to uniform enclosure surface temperatures belong to the same regression plane. Therefore the "Thermally Neutral Zone" developed in an earlier study for enclosure surfaces of uniform temperature is applicable for environments of the former type.

2. The regression planes, relating thermal sensation with air temperature and mean radiant temperature, developed for subjects exposed with radiation shape factors of 0.20 to a wall at 130 F and for subjects exposed to uniform enclosure surface temperatures were found to be significantly different, producing thermal sensation votes about 0.5 higher than expected in the case of the 130 F wall. Although the previously mentioned "Thermally Neutral Zone" is not applicable for thermal environments of the former type, it is felt it applies for less severe exposure to heated panels.

3. Thermally "neutral" subjects exposed with radiation shape factors of 0.12 to ceiling panels at 50 and 130 F and radiation shape factors of 0.20 to wall panels at 50 F experienced no significant discomfort which could be attributed to the asymmetry of the radiant field.

4. Thermally "neutral" subjects exposed with radiation shape factors of 0.20 to wall panels at 130 F experienced significant discomfort which was found to be caused by the asymmetry of the mean radiant temperature.

The radiation shape factors were determined by assuming the subjects to be of spherical geometry with centers two feet above floor level. Mean radiant temperature, MRT, was measured with the Honeywell 2-sphere radiometer. These results may not apply to situations where high temperature radiant sources are present.

Acknowledgements

This work was supported in part by ASHRAE RP 43. The authors appreciate this assistance as well as that of the chairman and members of TC 1.4 who directed the work in ASHRAE's behalf. In addition, this work was supported in part by Public Health Service Training Grant No. EH-68-602B from the Division of Environmental Health Services, Public Health Service, Department of Health, Education and Welfare.

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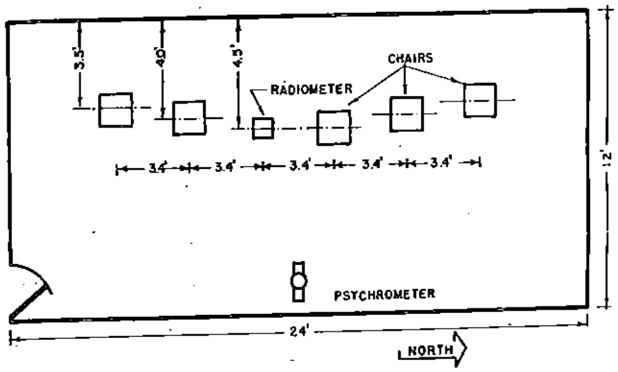

Fig. A-1. The Position of the Subjects and Radiometer for the Cool and Hot Wall Series

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APPENDIX A

Figures A-1 and A-2 show a floor plan of the seating arrangements used during the Cool and Hot Wall series and during the Cool and Hot Ceiling series.

APPENDIX B

The radiative and convective heat losses per unit area of the human body are represented by the following equation:

$$R + C_v = h_r f_r f_{cl} (t_{cl} - t_{mrt}) + h_c f_{cl} (t_{cl} - t_a) \qquad \text{(B-1)}$$

where

$R+C_v$ = Radiative and Convective heat losses, BTU/hr-ft^2

t_{cl} = the average temperature of the outer surface of the clothed body (°F)

t_{mrt} = the mean radiant temperature of the environment (°F)

t_a = the air dry bulb temperature (°F)

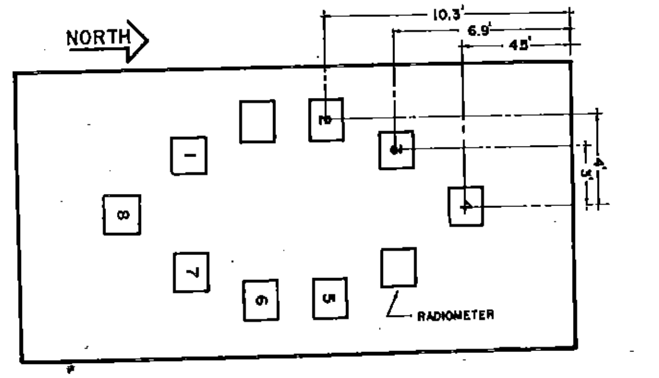

Fig. A-2. The Position of the Subjects and Radiometer for the Cool and Hot Ceiling Series

f_{cl} = the ratio of the clothed body surface area to the nude surface area (DuBois area)

f_r = the ratio of the effective radiation area of the clothed body to the nude surface area (DuBois area)

h_r = linear radiation heat transfer coefficient (BTU/hr-ft^2-F)

h_c = the convective heat transfer coefficient (BTU/hr-ft^2-F)

The value of f_{cl} was estimated as 1.1 and the value of f_r taken as 0.6 based on the results of Neilsen & Pederson (9) whose subjects' position and clothing attire closely resembled that of the present study. The value of h_r was calculated from the following equation:

$$h_r = \frac{\epsilon\sigma[(t_{cl}+460)^4 - (t_{mrt}+460)^4]}{(t_{cl}-t_{mrt})} \qquad \text{(B-2)}$$

where:

ϵ = the emissivity of the outer surface of the clothed body

σ = the Stephan Boltzman constant

with t_{cl} taken as 86 F, t_{mrt} as 80 F and ϵ equal to 0.95 the calculated value of h_r was found to be 1.04 BTU/hr-ft^2-F. The value of h_c was taken as the average determined from Winslow et al (10) and Colin and Houdas (11) with the relative air velocity taken as 25 fpm. Substituting these values, equation (B-1) can now be written as:

$$R + C_v = 0.686\,(t_{cl} - t_{mrt}) + 0.891\,(t_{cl} - t_a) \qquad \text{(B-3)}$$

The $R + C_v$ losses can be equated to the sensible heat transfer from the surface of the skin to the outer surface of the clothed body:

$$R + C_v \doteq \frac{\bar{t}_s - t_{cl}}{I_{cl}} \qquad \text{(B-4)}$$

where:

$\bar{t}_s$ = average temperature of the skin, °F

I_{cl} = total resistance to heat transfer from the skin to the outer surface of the clothed body. ($I_a = 0.59$ in these tests, or 0.52°F ft³ hr/Btu)

$\bar{t}_s$ = was determined from Fanger (8) while I_{cl} was measured as 0.59 clo.

The value of t_a equal to t_{mrt} necessary for predicted thermal "neutrality" was determined from the appropriate equation of Table 4. By equating equations (B-3) and (B-4) the value of t_{cl} was found allowing $R + C_v$ to be calculated from (B-3).

DISCUSSION

J. D. HARDY (John B. Pierce Foundation, New Haven, Conn.): One thing that bothers me about these asymmetrical tests is that they may not have lasted long enough. What I have in mind is the experience of Prof. Nielson and his group in Copenhagen. He studied his subjects 6 or 7 hrs a day while sitting between a warm wall on one side and a cold wall on the other. He continued the exposures for 3 weeks, 6 days a week. At the end of this time some to the people had muscle pains and even required hospital treatment. Their sensations however, agreed with yours. They were not different from "comfortable." It seems to me that the practical engineering problem is that if a person sits with a cold window on one side and something hot on the other for 40 hrs a week, week in and week out during the wintertime, will he or she have to go to the doctor? I wonder if you would comment on this?

DR. McNALL: I am familiar with that study. We probably should include that into our ASHRAE GUIDE AND DATA BOOK Chapter somewhere even though further work is necessary.

The purpose here was to look at the comfort, not health per se. Three hrs was the limit for these people to be under these conditions. The obvious practical thing for field application would be to have these people, in this environment, rotate somehow, by having them change their work position. I feel that the 3-hr period is sufficient, for the people used here, to determine the comfort and discomfort sensation.

R. L. BOYD (Singer Co., Auburn, N. Y.): Perhaps, as I have hypothesized for some time, the individual appreciates, perhaps utilizes, low levels of radiation more when needed most than when more nearly warm enough. Is any measurement of deep body temperature change contemplated in the situation giving about 30% more heat loss than predicted?

DR. McNALL: No, not yet anyway. We need further analytical work and further tests at this point to be sure why this takes place.

R. A. FERANCHAK (Westinghouse Electric, Pittsburgh, Pa.): I noticed in your Fig. 4, some of the subjects appeared to have a pad or book beneath their feet. Was this a controlled variable in both wall and ceiling tests?

DR. McNALL: Our standard uniform was without shoes. There is a practical reason for this as we could not afford shoes for every one and also we did not know what they would be wearing when they came for the experiment; therefore, we furnished them with a cotton type sweat sock. We have run tests where the floor was hot and cold. That is why the pad for their feet, for their personal comfort.

B. GIVONI (Army Research Environmental Medicine, Natick, Mass.): Were the computations of the radiation exchange based on the skin or clothing temperatures?

DR. McNALL: It is the average of the skin and exposed clothing temperature that is involved. No significant radiation at these temperature levels penetrates the clothing.