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Thermal Comfort (Thermally Neutral) Conditions for Three Levels of Activity

Satisfactory comfort conditions for a person at work vary, depending upon the rate of work (level of activity) and the amount of clothing worn. In general, the greater the degree of activity, the lower the temperature necessary for comfort. The effects of the level of activity on the thermal comfort of men and women have not been well established. Previous studies [1,2,3] of comfort conditions and work have concentrated mainly on determining the response of sedentary and slightly active subjects to dry bulb temperatures of 60 to 105 F and relative humidities from 20 to 90%.

The major purpose of the work reported in this paper was to determine the thermally neutral temperature and zone for men and women with activity levels resulting in metabolic rates of approximately 600, 800 and 1,000 Btuh* for the average male subject. In addition to the votes of thermal sensation, observations were made of several physiological responses to the work rates.

The ASHRAE standard[4] that specifies the environmental conditions that will provide year around thermal comfort for most people, normally clothed and engaged in sedentary or near sedentary activities, defines thermal comfort as "that condition of mind which expresses satisfaction with the thermal environment". The comfort zone, or zone of thermal neutrality, as defined in the ASHRAE Guide And Data Book[5] is the environmental condition where "the body is able to maintain a balance between heat production and heat loss without significant changes in any of the readily measurable indices of thermal comfort". The thermally neutral temperature was defined by the authors as the temperature desired most frequently by the subjects for thermal comfort within a zone of thermal neutrality.

The results of this study indicated that for metabolic rates of 600, 800 and 1,000 Btuh (approximately), the thermally neutral temperatures were 72, 66 and 60 F, respectively. Men and women preferred similar thermally neutral temperatures; however, the "comfort zone" for men at each metabolic rate included a wider range of temperatures than were included in the women's "comfort zone". Relative humidities of 25, 45, and 65% had little effect upon men and women's "thermal comfort" at the 600 and 800 Btuh (approximately) metabolic rates, but the relative humidity did affect the thermal comfort region for wommen at the 1,000 Btuh (approximately) metabolic rate.

EXPERIMENTAL FACILITIES

The experimental program was carried out in the KSU-ASHRAE environmental test chamber which was placed in operation at Kansas State University in November, 1963. This facility was originally located at the Society's Cleveland Laboratory (see

* Metabolic studies are not complete and will be the subject of a subsequent paper.

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Fig. 1 Male and female subjects in standardized clothing consisting of cotton twill shirt, trousers and sweatsocks

Ref 6 for a description of the room at that location). A complete description of the present facility now located in the Institute for Environmental Research Building on the Kansas State University campus was included in the recent paper, A Temperature-Humidity Chart for Thermal Comfort of Seated Persons, by Nevins et al.[2]

TEST SUBJECTS

The test subjects,* 210 males and 210 females, with an average age of 20 and 19 years, respectively, ranged in age from 17 to 25. All subjects were volunteers and received $5.00 for participation. No subject was allowed to participate more than once at a single activity level. During each activity cycle, the subjects were exposed to the thermal conditions for three hours in groups of 10, 5 men and 5 women.

CLOTHING

Nude subjects were used in many of the previous investigations of human comfort. From the physiological and statistical point of view, the use of nude subjects has an advantage: the elimination of clothing as an experimental variable. However, the ultimate application of comfort study work is to men and women working in a temperate climate where clothing is worn both winter and summer. Therefore, although clothing presents an additional variable that must be considered, clothed subjects were used in this study. To minimize variation due to clothing, all subjects were clothed in cotton twill shirts and trousers (similar to clothing worn by service station attendants) with the shirts worn outside the trousers. Male subjects wore cotton undershorts or jockey shorts, but no undershirts or T-shirts. Brassieres and underpants were worn by the women. All subjects wore woolen socks without shoes. It was felt that this type and weight of clothing was typical of that normally worn by male persons working at or near the activity levels investigated. The insulating value of the clothing was measured by the Army Research Institute of Environmental Medicine and by the Institute for Environmental Research, Kansas State University, and was found to be 0.52 clo. The authors believe that the clothing normally worn by men and women indoors, while working within the range of activity levels investigated, is approximately 0.5 clo. Fig. 1 shows a typical male and female subject in the standardized clothing developed.[2]

*Healthy, Kansas State University college students.

EXPERIMENTAL DESIGN

Three activity levels representing metabolic rates of approximately 600 (low activity level), 800 (medium activity level), and 1,000 (high activity level) Btuh for average male subjects were selected. These rates represent step increases of the sedentary male metabolic rate of approximately 400 Btuh and (as described in the ASHRAE Guide And Data Book) are felt to be representative of distinct daily activities that a man or woman would experience in indoor environments. Examples of practical activities or occupations resulting in similar metabolic rates are shown in Table I.[5,7,8]

Table I. Typical Examples of Activities and Occupations for the Metabolic Rates Investigated

Metabolic Rate* Btuh	Activities and Occupations
600	Sitting, moderate arm and leg movements, driving car in traffic, housemaid, typewriting rapidly, ironing, and washing floors
800	Sitting, heavy arm and leg movements standing, moderate work at machine or bench, shoemaker, and walking (3 mph)
1000	Walking about, with moderate lifting or pushing, carpenter, metalworker and industrial painter

*Approximate value for the average male.

The basic experimental design consisted of nine temperature-humidity combinations (shown in Table II) for each activity level. Previous data from the ASHRAE Guide And Data Book were analyzed and heat transfer calculations were made on model human body shapes to design these test combinations. The tests were randomized as to time of day (afternoon or evening). Mornings were avoided since previous work[2] indicated the results of the morning tests were significantly different from afternoon and evening tests. This was probably due to the effect of diurnal metabolic cycles. Several preliminary tests were run to verify the predictions with human subjects. For each activity level, the central temperature of the three was selected as that of the predicted thermally neutral or "thermal comfort" temperature. The 6 F interval was chosen since it represented approximately a unit thermal sensation vote difference by subjects in previous tests.[2] The three relative humidities (25, 45, 65%) were chosen because they include the practical extremes for normal environmental control. The same relative humidities were used for each activity level, and the humidity effect on thermal sensation was predicted to be small or negligible. Subjects were randomly assigned to the nine possible treatments, resulting in a completely randomized design for each activity.

Table II. The Experimental Design of Temperature - Humidity Combinations for the Three Levels of Activity

RH	DBT F 66	72	78
25	E	E	A
45	A	A	E
65	A	E	A

Low Activity Level

RH	DBT F 60	66	72
25	A	E	A
45	E	A	E
65	A	E	E

Medium Activity Level

RH	DBT F 54	60	66
25	A	A	E
45	E	A	E
65	A	E	A

High Activity Level

A = Afternoon Test
E = Evening Test

Using a modified step test for each activity level, a stand-walk cycle was developed by varying the stand period and using the 5 min walk over two 9-in. steps (shown in Fig. 2). A physical description of the step test is similar to that as described for the Master two-step test.[9] The Master two-step test has been demonstrated to have a sound physiological basis and to impose an equal energy demand on subjects of different age and weight.[10] Performance of the Master two-step test requires an energy cost, as measured by oxygen consumption, similar to that of a man walking fast (4.8 mph), climbing, and descending stairs (two flights/min) or doing deep knee-bend exercise (33/min).

The resulting cycles were: stand 25 minutes - walk 5 min for the low activity level; stand 10 min - walk 5 min for the medium activity level; stand 5 min - walk 5 min for the high activity level.

Fig. 3 is a facsimile of the thermal sensation ballot used by the subjects. It shows the thermal sensation scale used. It is similar to the thermal comfort scale developed by Houghton and Yaglou[11] with "comfortable" replaced by "neutral" for a No. 4 vote, as suggested by Gagge and Hardy of the John B. Pierce Laboratory, New Haven, Conn. Statistical analysis using sedentary test data was used to verify the validity of the thermal sensation scale and to justify its use. Appendix A details this justification. This scale is felt to be more scientifically descriptive and adaptive to non-uniform thermal effects planned for the future. (In future studies, it may be possible for a subject to feel thermally neutral, yet uncomfortable due to

Fig. 2 Male subject during 5 min walk period on two 9-in. steps

Subject
Name ____

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1. cold
2. cool
3. slightly
4. neutral
5. slightly
6. warm
7. hot

Fig. 3 Ther

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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. 3 Thermal sensation ballot

the non-uniformity. In these cases, thermal neutrality and comfort will be evaluated separately.)

Throughout the tests wall temperature was maintained equal to the air temperature. Previous analysis of air motion within the room and in the vicinity of the subjects showed that air movement, as measured by an anemometer, was between 20 and 30 fpm for all tests.

In all cases, the test exposure was three hr at the same activity level and thermal condition. The afternoon tests were conducted from 1:30 pm to 4:30 pm and the evening tests from 6:30 pm to 9:30 pm. All tests reported in this paper were conducted during February, March, May and September, 1966.

PROCEDURE

The subjects reported for the tests and dressed in the special clothing. They then entered the pre-test room. The subjects' age, height, weight, pulse rate and oral temperature were taken by a registered nurse. No subject was permitted to participate whose temperature was above 99F. The subjects stayed in the pre-test room for 30 min; during this time they were indoctrinated regarding the purpose and conduct of the study and the method of voting using the thermal sensation ballot. Appendix B contains the indoctrination information.

It should be noted that even though 10 subjects participated in each test, 12 were scheduled to permit a male and female substitute in the event a subject had an elevated temperature or failed to report for the test. Extra subjects were then used as assistants for the experiments.

Upon entering the test chamber, subjects were assigned positions at the tables (Fig. 4) and drinking cups for the duration of the test. The activity cycle then began with the stand period followed by the walk period. This cycle continued for three hr. Subjects were allowed to read, study, play cards, and quietly converse while standing. An enunciator (1 "click" per sec) and a stand-walk sign (see Fig. 2) were used to pace the walk and to indicate the stand-walk sequence. The pulse rate of each subject was taken just after he completed a walk period, and again just before he started his next walk period during the first hr of the test. This procedure was repeated during the third hr of the test. These data were compared to determine the physiological stress imposed on the subject. The subjects were allowed to drink as much water as desired with each subject's consumption being recorded by the nurse. No food was consumed by the subjects during the tests. Subjects, once they had entered, did not leave the test chamber until the test was completed.

Approximately one hr after entering the test chamber, the subjects reported their impression of thermal sensation by circling the number on the ballot (Fig. 3) that described their thermal sensation. After this vote was taken, the ballots were collected and the votes were tallied. One half hr later, the second vote was taken and recorded. This was repeated after each of the three subsequent half hr periods until five votes had been taken. The voting times were approximately 1.0, 1.5, 2.0, 2.5, 3.0 hr after entering the chamber.

All votes were taken during the stand period. The exact time of voting was determined from a pilot study outlined in Appendix C. This was necessary due to the cyclic nature of the activity during the tests, which caused a variation in the thermal sensation with time. For the three activity levels the votes were taken 12 min after walking for the low activity level, 4 min after walking for the medium activity level and 2 min after walking for the high activity level.

At the end of the third hour, pulse rates were taken for all subjects, and they reentered the pre-test room where final weights were taken. The amount of water remaining in the cups was weighed.

RESULTS

A statistical analysis was made of the data. The method of least squares was used to fit a surface through the means of the thermal sensation votes in the temperature-humidity plane. A probability

Fig. 4 Male subjects during stand period of the stand-walk cycle

of 0.05 (5%) was used for the tests of significance.* The following results for each activity were obtained from a multiple regression analysis of the means of the final thermal sensation votes.

A. Low Activity Level

1. The equations for the estimated mean thermal sensation vote as a function of temperatures and humidity were:

$$Ym = -2.755 + 0.09722\ T \quad (1)$$
$$R^2 = 0.734 \quad Syx = 0.334$$

$$Yf = 113.769 - 3.219\ T + 0.0235\ T^2 \quad (2)$$
$$R^2 = 0.949 \quad Syx = 0.252$$

where,

- Ym = Estimated population mean vote for college-age males
- Yf = Estimated population mean vote for college-age females
- T = DBT, F
- R^2 = Square of the multiple correlation coefficient of determination (Percent of variance accounted for by the joint action of the independent variables)**
- Syx = Standard error of estimate (A measure of the variation from the estimated mean vote)***

2. There was a strong linear effect of temperature for the males. Quadratic effects of temperature and the linear effect of relative humidity were not significant at the 5% probability level. While relative humidity effects might be detectable over a wider range of humidities, the assumption of linearity with respect to temperature only will give an excellent approximation for the males.

3. A significant curvilinear effect of temperature was detected for females at the 5% probability level. The effect of relative humidity was not significant.

B. Medium Activity Level

1. The equations for the estimated mean thermal sensation vote as a function of temperature and humidity were:

$$Ym = -0.602 + 0.06895\ T \quad (3)$$
$$R^2 = 0.706 \quad Syx = 0.334$$

$$Yf = -4.292 + 0.1242\ T \quad (4)$$
$$R^2 = 0.783 \quad Syx = 0.491$$

2. A strong linear effect of temperature resulted for both males and females. Although the linear effect of relative humidity and the quadratic effects of temperature were not statistically significant at the 5% probability level, they did appear sporadically. Therefore, these effects cannot be completely discounted and further tests over a wider range might show significance.

C. High Activity Level

1. The equations for the estimated mean thermal sensation vote as a function of temperature and humidity were:

$$Ym = -1.211 + 0.0833\ T \quad (5)$$
$$R^2 = 0.343 \quad Syx = 0.360$$

$$Yf = -10.360 + 0.2111\ T + 0.0408\ H \quad (6)$$
$$R^2 = 0.833 \quad Syx = 0.603$$

where H = Relative humidity in %.

2. A linear effect of temperature was detected for the males at the 5% probability level. The linear effect of relative humidity and the quadratic effects of temperatures were not significant at the 5% probability level.

3. There was a strong linear effect on temperature and a smaller linear effect of relative humidity for females. The assumption of linearity gave an excellent approximation.

The mean vote at the end of the third hr of testing for the male and female subjects at each activity level is shown in Tables III, IV and V.

Thermal sensation lines are shown in Fig. 5 for males and in Fig. 6 for females, for the three activities. Also plotted on Figs. 5 and 6 are the corresponding lines for sedentary activity as defined by Nevins et al.[2] Because rh was not a significant variable the three mean votes at each DBT were combined and their means are presented in Figs. 5 and 6.

DISCUSSION

This study is a continuation of the ASHRAE comfort studies carried on by the Institute for Environmental Research at Kansas State University. As stated in previous papers,[2,12] thermal comfort is an extremely nebulous variable. There is a multitude of variables that may influence the reactions of the subjects. This study attempted to control as many of these variables as possible,

*Non-significance meant the hypothesis being tested could not be rejected, and that the difference could be attributed to random, uncontrolled variation. Significance meant the hypothesis was rejected and that something has happened in the experiment that would be expected to happen by chance, less than one in twenty trials. Therefore, some difference in mean votes does exist that cannot be accounted for by random, uncontrolled variation. Thus, the difference observed appears to be the result of the different experimental condition.

**Maximum $R^2 = 1.00$. For $R^2 = 0.80$, 80% of whatever makes one subject vote differently than another is explained by the combination of independent variables given in the estimated mean vote equations. The remaining 20% of the variance in mean votes must be attributed to factors not measured in the test.

Table III. After Thre Level for

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25
45
65

RH
25
45
65

Table IV. After Thre Level for

RH
25
45
65

RH
25
45
65

Fig. 5 The four levels

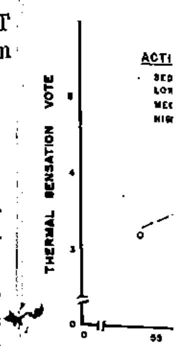


Table III. The Mean Thermal Sensation Vote After Three Hour Exposure to the Low Activity Level for Males and Females

DBT F — Males

RH	66	72	78
25	4.0	4.0	4.4
45	3.4	4.0	5.2
65	3.8	4.2	5.2

DBT F — Females

RH	66	72	78
25	3.4	3.8	5.2
45	3.6	4.0	5.8
65	4.0	4.2	6.0

Table IV. The Mean Thermal Sensation Vote After Three Hour Exposure to the Medium Activity Level for Males and Females

DBT F — Males

RH	60	66	72	78
25	3.4	4.0	4.4	5.0*
45	3.6	4.4	4.2	4.5*
65	3.2	4.0	4.6	4.7*

DBT F — Females

RH	60	66	72	78
25	3.2	4.0	4.6	5.9*
45	3.0	4.0	4.8	5.5*
65	2.8	4.5	4.4	4.7*

Fig. 5 Thermal sensation vote vs DBT for males at four levels of activity after three hr exposure.

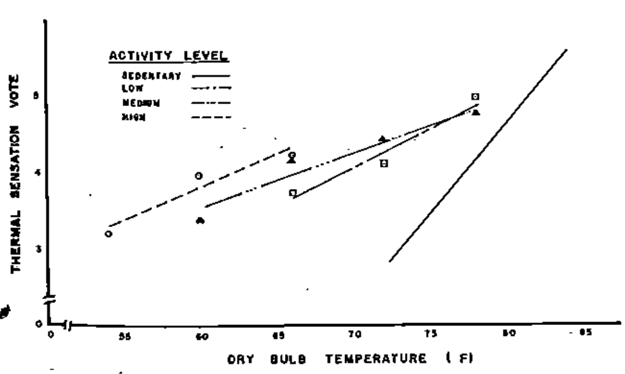


Table V. The Mean Thermal Sensation Vote After Three Hour Exposure to the High Activity Level for Males and Females*

DBT F — Males

RH	54	60	66
25	3.1	3.2	4.2
45	3.2	3.8	4.2
65	3.3	4.4	4.9

DBT F — Females

RH	54	60	66
25	2.7	3.3	4.2
45	2.2	4.4	5.4
65	3.7	4.8	6.6

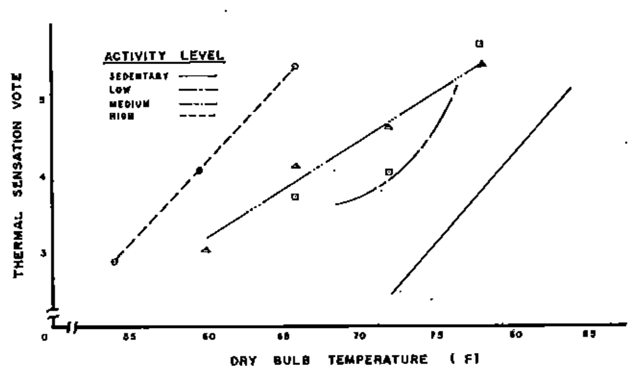
*Two tests were run for each temperature-humidity combination. The average of the results is presented.

and thereby increase the overall validity of the findings.

420 untrained observers served as subjects. Untrained observers were preferred over trained observers for the reasons stated by Nevins, et al.[2] First, they comprise a larger sample, making possible a more valid generalization; second, untrained subjects are more representative of the general population than are trained professional observers; and, for this experimental design, the order of presentation of the test conditions is not important for statistical validity.

The criteria established by Nevins et al.[2] for control of the human factors (as defined by Rohles[12]), which must be considered when conducting environmental research on human subjects, were used for this study. This also provided a valid means for comparing the results between

Fig. 6 Thermal sensation vote vs DBT for females at four levels of activity after three hr exposure.



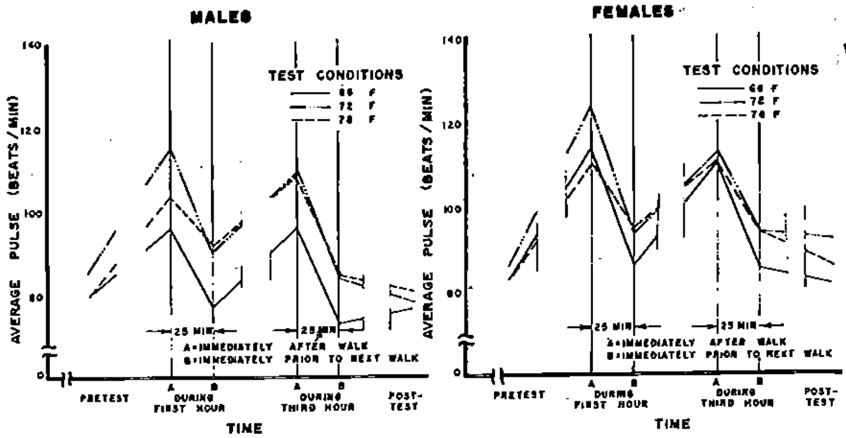


Fig. 7 Pulse rate variations for males and females during the low activity level tests

activity levels. Rohles'[12] reciprocative factors, activity, clothing, exposure time and number of subjects by sex, were identical for each thermal condition within an activity level. The organismic factors of basal metabolic rate and diet were not considered; however, biological rhythmicity was accounted for by conducting half of the tests in the afternoon and half in the evening. In addition, the variance in age was small. The physical factors, temperature and humidity, were used as the independent variables for the study.

Enlargement of the experimental design and reruns at given temperatures were necessary in the medium and high activity levels so that observed variability could be more fully explained. This included adding the 78F test to the medium activity level design. In some cases, information received initially was not sufficient for proper statistical analysis; therefore, reruns were required to verify initial findings. However, a duplication of all test conditions was not felt justifiable.

Pulse rate and evaporative heat loss data were analyzed to provide physiological information of the subjects' reaction to the temperature and humidity conditions at each level of activity. This analysis was not begun until the first series of tests (medium activity level) was nearly completed; therefore, a complete analysis of all conditions was not available. However, from the data obtained, trends were established and have been presented to help explain the variability seen in the thermal sensation vote lines of Figs. 5 and 6.

Figs. 7, 8 and 9 give the pulse rate variations for both sexes during each activity cycle. The effect of relative humidity on pulse rate at the temperature investigated was not statistically significant. Therefore, the figures contain the variations with temperature only, over the three hr test period. Two recovery periods (stand portion of activity), representing a sample of the first and third hr subjects' responses to the activity levels are shown.

The average pre-test pulse rate for male subjects was 83 beats per min and 84 beats per min for female subjects. For each test conducted, the final average pulse rates were slightly higher than the pre-test pulse rates for males and females with females showing a greater increase than males (but not significantly different at the 0.05 probability level).

Fig. 7 shows the similarity of pulse rate variations for males and females participating in the low activity level tests. Significant deviation between the pulse rates at 66 F and 72 F was noted for males. No indication of the strong temperature effect for females as given in Eq 2 was seen in Fig. 7. For males, the combined average pulse rate immediately after walking during the first hr was 104 bpm (beats per minute) and 104 bpm during

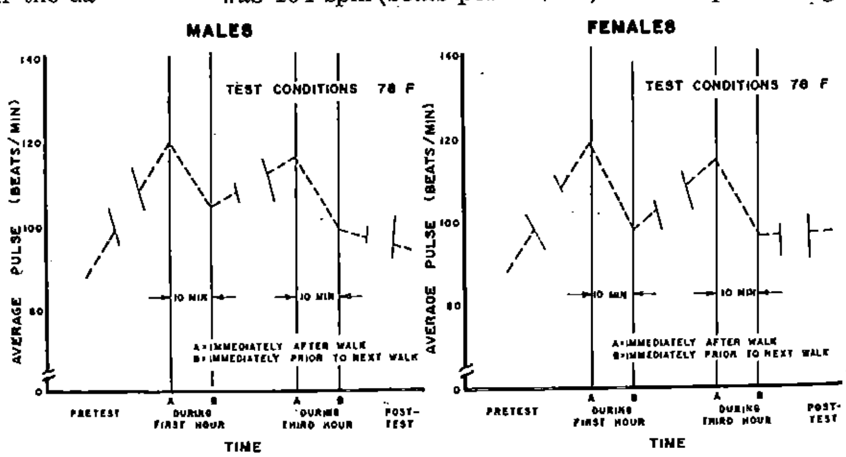


Fig. 8 Pulse rate variations for males and females during the medium activity level tests

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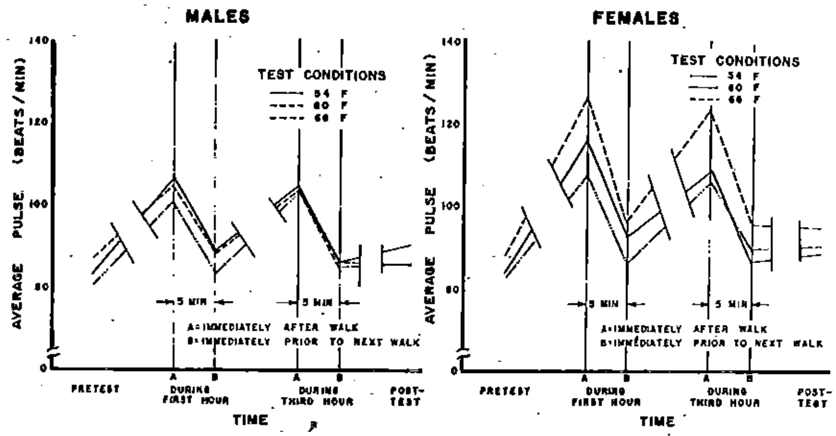

Fig. 9. Pulse rate variations for males and females during the high activity level tests

the third hr, while for females it was 112 bpm and 111 bpm. Immediately prior to walking for males during the first hour it was 86 bpm and 80 bpm during the third hr. For females, it was 91 bpm and 90 bpm.

The decision to collect pulse rate data was made after 12 medium activity tests had been conducted; therefore, only the results of the final tests in the series are included in this paper. Fig. 8 shows males and females having similar pulse rate profiles for the highest dry bulb temperature investigated at the medium activity level. The uniformity of the average pulse rates from the first hour to the third indicates that at this activity level neither males nor females were stressed significantly at the various temperatures investigated. The similarity of the thermal sensation lines in Figs. 5 and 6 for the medium activity level gives strong support to the validity of this conclusion.

Comparison of the average pulse rates for males and females in Fig. 9 shows that the three temperatures caused little variation in the pulse rate profile for males for the high activity level, while a significant effect of temperature was seen for females. This difference in male and female profiles corresponds with the significant difference between male and female thermal sensation votes at the high activity level, as seen in Figs. 5 and 6. This variation in pulse rates and voting indicates that the high activity level was causing a greater physiological stress in the female subjects than in the males. The combined average pulse rate for men immediately after walking during the first hr was 104 bpm and 103 bpm during the third hr; for females it was 116 bpm and 112 bpm. Immediately prior to walking during the first hr the pulse rate was 87 bpm for males and 86 bpm during the third hr; for females it was 91 bpm and 90 bpm.

Although some deviations in pulse rate between temperature levels within an activity level were significant, the results were not consistent over the three activity levels. Therefore, the average decrease in pulse rate for all tests within the stand portion of a cycle is given in Table VI. No significant difference in pulse rate recovery was seen when comparisons were made between males, females and activity levels; however, a trend was observed indicating that males increased their recovery ability during the three hr tests while females' pulse rate recovery decreased. This would support the conclusion that the females were physiologically stressed somewhat more than the males, especially in the high activity tests. Female pulse rate recovery appears to be greater than the male for the three activity levels. However, it should be noted that female pulse rates were approximately 10% higher than males immediately after walking. Thus, a larger range was available for recovery by females.

Heat loss by evaporation, normalized for a unit body area, was less for females than males, although both were participating in the same test, wore similar Kansas State University clothing and worked at the same task. The 10 to 25% difference shown in Fig. 10 was consistent throughout the tests. For the reasons stated previously, only one set of data was collected for the medium activity level; therefore, it was not possible to make an overall analysis of evaporative heat loss. However, the trends observed have been indicated. From Fig. 10, it was observed that heat loss by evaporation increased for males and females as the dry bulb temperature increased for a given activity level. This observation agreed with previous results published by Humphreys et al.[13]

Table VI. The Average Decrease in Pulse Rate During the Stand Portion of Activity Tests Just After a Five Minute Walk Period

Average Decrease in Pulse Rate After Stand Time of:	Males: During 1st Hr of Test (Beats per min)	Males: During 3rd Hr of Test (Beats per min)	Females: During 1st Hr of Test (Beats per min.)	Females: During 3rd Hr of Test (Beats per min.)
5 min	17.2	18.1	25.0	22.2
10 min	15.5	17.3	20.7	18.1
25 min	18.4	21.6	24.3	20.3

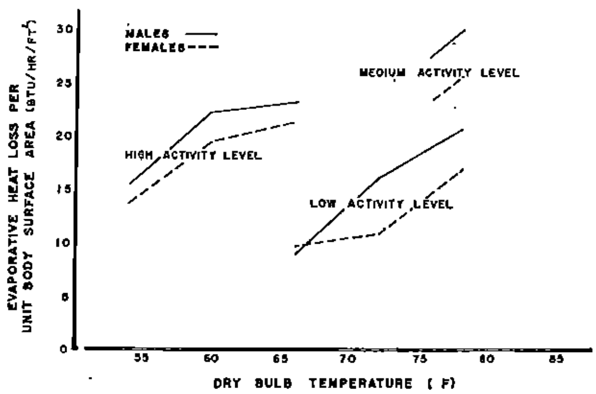

Fig. 10 Evaporative heat loss per unit body surface area vs test conditions (dry bulb temperature) for the three activity levels for both males and females

The accuracy of the three activity levels in approximating the desired 600, 800 and 1,000 Btuh activity levels at the designed neutral vote condition for males was verified by using the evaporative heat loss and applicable heat transfer equations.[14,15] For heat transfer calculations, cylinders with the dimensions of the average sized male and female subject were assumed. Table VII gives the results for the average male and female subject participating in the test. Conduction losses were assumed negligible. The approximately 190.0 Btuh difference (20% - 30%) in total metabolic heat loss between males and females shown in Table VII may be attributed in part to the difference in average body sizes and the average external work required to perform the three activity cycles. From DuBois,[16] it was found that the average basal metabolism for 20 year old females was 8 to 10% less than for males of similar age. Combining this fact with the observed physical differences in males and females (14% for body surface area and 20% for body weight), a difference of this amount could be expected. However, it is possible that females were storing some heat while the males were able to maintain homeostasis for each activity level. The lower metabolic rate and the possibility of heat storage may explain why females were more sensitive to thermal conditions for each activity than the males. Body heat storage caused by the body generating more heat than is dissipated per unit of time will influence a person's sensitivity to thermal changes. A lower metabolic heat production rate allows thermal changes to have a greater affect on the subject because less heat is available to meet the demand imposed by the environment.

Figs. 5 and 6 are presented for comparison of the three activity level thermal sensation neutral lines and the dry bulb temperatures. Using data from A Temperature-Humidity Chart for Thermal Comfort of Seated Persons by Nevins et al.,[2] a thermal sensation line for sedentary males and females was added to each of the figures.

Fig. 5 shows that men became less sensitive to dry bulb temperature changes as the activity level was increased. After nine tests were completed, at the high activity level, no temperature or humidity combinations were found statistically significant for males at the 5% probability level and 20% of the males variability could be explained. Therefore, a second series of nine tests at the high activity level were conducted. The results of the two series of tests were combined and the effect of dry bulb temperature was found to be significant at the 5% probability level. However, only 34% of the data variability was explained by the least squares solution (Eq 5). Analysis of the mean thermal sensation votes (Table V) gave evidence that a temperature humidity interaction, although not statistically significant at the 5% level, was present.

Table VII. Metabolic Heat Loss for the Average Male and Female Subject Near the Thermal Neutrality Condition for Three Activity Levels

Subject	Geometries and Weights for Heat Loss Calculations			
	Ht (In)	Wt (Lb)	Dia (In)	Body Surface Area Sq Ft
Average male subject	69.8	163.4	13.55	20.63
Average female subject	64.8	130.4	12.54	17.75

	25 Min Stand 5 Min Walk Cycle Dry Bulb Temperature 72 F		10 Min Stand 5 Min Walk Cycle Dry Bulb Temperature 66 F		5 Min Stand 5 Min Walk Cycle Dry Bulb Temperature 60 F	
Metabolic Btuh Heat Loss	Male	Female	Male	Female	Male	Female
Evaporative (Measured)	335	195	382	267	471	350
Radiation and Convection (calculated)	357	307	430	370	495	426
Total Btuh	692	502	812	637	966	776

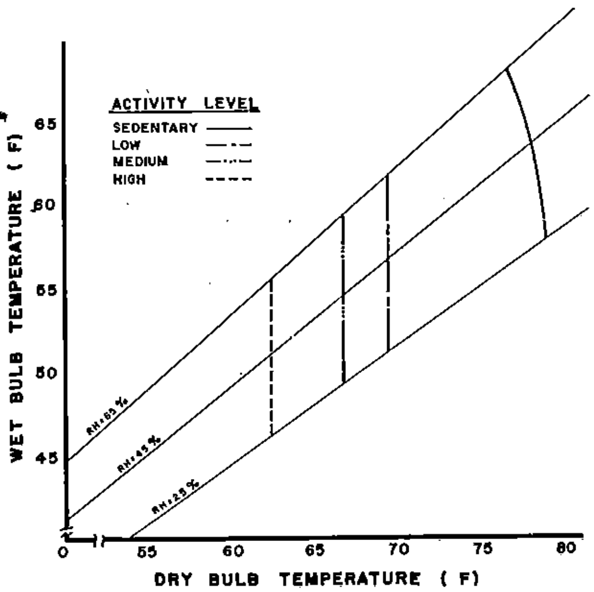

Fig. 11 Lines of thermal neutrality for four levels of activity for males

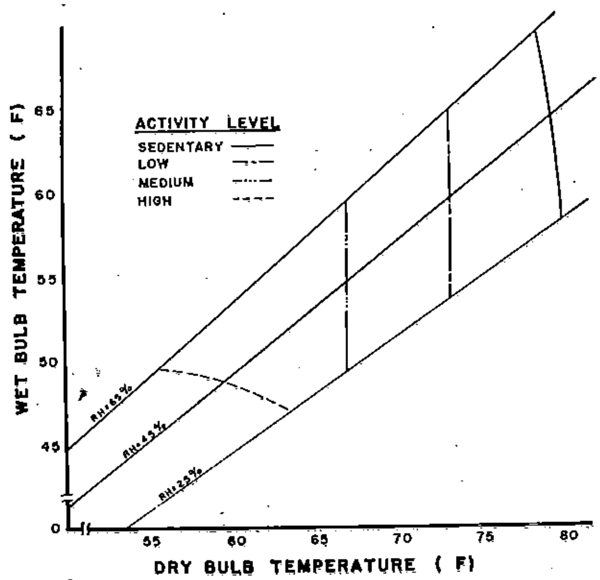

Fig. 12 Lines of thermal neutrality for four levels of activity for females

Because of the wide distribution of mean votes, as seen in Table V, more observations at each of the nine test conditions will be required to better explain the remaining data variability. Presently, the assumption of linearity with temperature gives the best description of male thermal sensation voting at the high activity level.

For the three activity levels, a range of 25 to 65% relative humidity caused no significant effect upon male comfort, although previous work with sedentary males by Nevins et al.[2] did indicate a small temperature-humidity interaction. Thus, the effect of relative humidity on human comfort appears to have less importance, both at temperatures below the sedentary thermal neutrality condition and within the thermally neutral zone for activity levels higher than sedentary.

The results for the female subjects were not as conclusive as those indicated for males; however, a strong temperature effect was observed for each activity level. At the low activity level, a strong quadratic effect of temperatures was indicated. The reason for quadratic temperature effect cannot be explained, but it was felt that future research with a larger temperature difference and a greater number of observations may indicate only a linear effect for temperature and a possible linear effect of relative humidity.

The high activity level produced some unexpected and unexplainable results for females. Eq 6 and Figs. 6 and 12 indicate a strong linear effect of temperature and relative humidity. A decrease in temperature and relative humidity sensitivity similar to that observed for males was expected; however, the data showed that females were extremely sensitive to temperature and relative humidity changes. Referring to Fig. 9, the noticeable deviation between female and male pulse rates offers a plausible physiological reason for the increased female sensitivity. Fatigue, causing physiological stress, may have influenced the response of the female subjects participating in the high activity level.

Although the relative humidities investigated for this paper were found to have only a small effect on the subject's thermal sensation voting, it was noted that for each activity level, when the temperatures investigated within a thermally neutral zone were higher than the thermally neutral temperature for that activity, both male and female mean votes at those temperatures were influenced by the relative humidity. The 65% relative humidity would have the highest mean vote while the mean vote for 25% relative humidity would be the lowest. This observation was not seen at temperatures near or below the thermally neutral temperature. Therefore, it is probable that future comfort studies at temperatures above the thermally neutral zone for an activity level will find that relative humidity is a significant parameter, whose effect on a subject's thermal sensation is similar to that found for sedentary subjects at temperatures above the sedentary thermally neutral zone.

The thermally neutral zone for each activity level, by definition, includes those temperatures within one-half vote of the thermally neutral temperature lines shown in Fig. 5 for males and Fig. 6 for females. Shown in Table VIII are the thermally neutral zones for males and females at the three activity levels and for relative humidities between 25 and 65%.

Table VIII. The Thermally Neutral Zones* for Males and Females for Three Activity Levels with Relative Humidity Between 25 and 65%

Activity Level	Males F	Females F
Low	64 - 75	67 - 75
Medium	60 - 73	63 - 71
High	56 - 68	57 - 62

*The thermally neutral zone includes those temperatures within one-half vote of the thermally neutral temperature lines.

The results of this study are presented in Figs. 11 and 12 for college-age males and females wearing standard clothing and exposed for three hr to the three activity levels studied. In addition, the line determined by Nevins et al.[2] for sedentary activity is shown in both figures. The lines for the four activity levels are recommended as the design criteria for human thermal neutrality.

ACKNOWLEDGEMENT

The authors wish to acknowledge the support of ASHRAE through RP 43, the help and encouragement of the members of TC 1.4, Physiological Research and Human Comfort, and the KSU-ASHRAE Advisory Board, who helped direct the work. In addition, the assistance given by Professor Arlin Feyerherm, Department of Statistics, Kansas State University, who consulted on the statistical design and analysis, is acknowledged.

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APPENDIX A

Justification for Substitution of "Neutral" for "Comfortable" in the Thermal Sensation-Vote Scale

Four sedentary conditions that were previously investigated by Nevins, et al[2] and within the comfort zone, were selected at random for the justification. They were: 1. 76 db, 75 rh; 2. 78 db, 25 rh; 3. 78 db, 45 rh; and 4. 80 db, 15 rh. The tests were repeated in the manner described in Nevins et al,[2] with the only change being the substitution of "neutral" for "comfortable" in the thermal sensation vote scale. A total of 80 subjects, 40 males and 40 females, were used. Table A-1 shows the aggregate observed thermal sensation votes of the subjects after three hr exposure to the environmental conditions.

The null hypothesis tested was that under identical thermal conditions there was no difference between the "effectiveness" of the two thermal sensation vote scales, so that the proportion of cold, cool, slightly cool, neutral, slightly warm, and hot votes on both scales would be the same. Statistical analysis through the use of chi-square techniques revealed that the substitution caused no significant change in the subject's thermal sensation vote at the 5% probability level.

Table A-1. Sedentary Subjects' Thermal Sensation Votes After a Three Exposure to Four Different Environmental Conditions in the Comfort Zone

Title of No. 4 Vote	Vote: Slightly Cool 3	4	Slightly Warm 5
"Comfortable"	8	28	4
"Neutral"	6	23	11

APPENDIX B

Indoctrination Information Given Orally to the Test Subjects

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that various temperature and humidity conditions have on exercising human beings. As soon as preparations are completed in the pre-test room, we will then take you into the test room next door. Stand at one of the tables until you are instructed to start walking up and down the steps provided. You will then walk for 5 min and return to your place at the table until instructions are again given.

At the end of the first hour, and each half hour thereafter, we will ask you to indicate your impression of the thermal sensation that you feel. We will provide a ballot that lists seven possible thermal sensations. (Cold, cool, slightly cool, neutral slightly warm, warm, hot). Circle the number that best describes your thermal sensation. The ballot will be picked up each time after you vote. Remember, vote the way you feel. Let no one else influence your vote!

While you are in the room you may play cards, study or engage in quiet conversation. You may smoke but we ask that you keep your smoking to a minimum.

When you are finished, we would like to have you go to your respective dressing rooms and get dressed. Girls, put your shirts, trousers, and socks in one pile in your dressing room. Boys, drop your uniforms and socks down from upstairs on the table by the pre-test room door. These will be picked up by the nurse and counted and placed in the laundry hamper. Do not leave uniforms in the upstairs restroom.

All persons participating in these tests will sign a receipt for your pay, $5.00, which will be given to you at the end of the test.

Are there any questions?

APPENDIX C

Analysis of Thermal Sensation Vote Variation with Time

In this study, the energy expenditure of the subject at the various activities was cyclic in nature. Therefore, the exact time during the cycle that a subject should vote must be considered. In these experiments, under "comfortable" conditions while walking, more heat is produced than is required for homeostasis. When the subject stops walking and stands quietly, he transfers the excess heat to the surrounding atmosphere. The gain and loss of metabolically generated heat produces a temperature gradient that a subject can detect and describe as feeling warmer or cooler. Pilot studies on metabolic production rates done in the Environmental Research Institute at Kansas State University (February 1966) revealed that when a subject was asked to express his thermal sensations on the thermal scale, repeatedly after short intervals of time, the series of responses varied (as shown in Fig. C-1).

Three 3-hr tests were conducted with 10 subjects, 5 males and 5 females, participating in each test. Room conditions and activity levels were as follows:

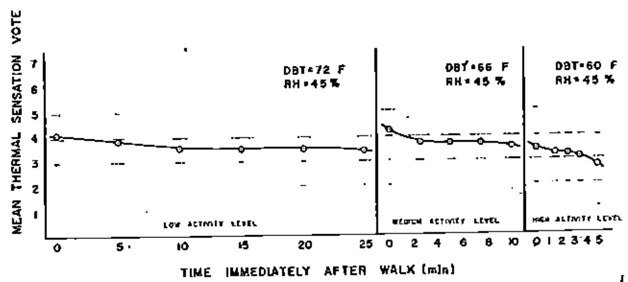

Fig. C-1 Mean thermal sensation vote vs time after completion of walk period for three levels of activity

Test A - 60 F, 45 RH and High Activity Level (Walk 5 min -Stand 5 min)

Test B - 66 F, 45 RH and Medium Activity Level (Walk 5 min - Stand 10 min)

Test C - 72 F, 45 RH and Low Activity Level (Walk 5 min - Stand 25 min)

The room conditions selected represented an expected thermal neutrality condition for each activity level, thus minimizing possible biasing from extreme room conditions. Each test was performed in the manner described in the text of this paper.

Votes were taken during three portions of each test at approximately 0.15, 0.30 and 1.0 hr after the tests began. Normal voting procedure was used for the completion of the test. Five votes were taken during the 5-min stand period of Test A. The times were 0.0, 1.5, 2.5, 3.5 and 5.0 min after the subject stopped walking. Five votes were taken during the 10-min stand period of Test B. Voting times were 0.0, 2.5, 5.0, 7.5 and 10.0 min after the subject stopped walking. Six votes were taken during the 25-min stand period of Text C. Voting times were 0.0, 5.0, 10.0, 15.0, 20.0 and 25.0 min after the subjects stopped walking. The voting time profiles for the three activity levels at approximately one hr after the test began are shown in Fig. C-1.

The mean vote of each cycle showed the effect of body cooling on the subject's thermal sensation vote. A time history analysis of the mean votes indicated that when the initial vote was taken, the subject's metabolic heat production was greater than that required for standing. Thus, heat was

Table C-I. The Exact Times that a Subject Should Vote After Completing the Walk Period for the Three Activity Levels.

Activity Level	Time After Completion of the Walk Period Min
High	2.0
Medium	4.0
Low	12.0

dissipated through vasodilation and skin evaporation. This excess energy caused the subject to describe himself as slightly warmer than the mean. Continued standing enabled the body metabolic mechanisms to stabilize the heat loss per unit time and thus give a plateau effect (constant means) as seen in Fig. C-1. Finally, near the end of each stand period, lowered mean votes were seen, indicating that body metabolism during standing was not sufficient to maintain homeostasis with the environmental conditions.

The plot of mean votes was non-linear; however, the extremes did not deviate from the mean over 0.5 vote, and deviations above and below the mean were approximately equal. Therefore, linearity was assumed, and the time intervals selected to specify the exact times that a subject should vote, after completing the walk period of each cycle, in order to obtain the most valid vote for the period, are listed in Table C-1.

DISCUSSION

A. P. GAGGE, New Haven, Conn. (Written): The authors are to be congratulated on their excellent first results on relating levels of exercise and thermal sensation.

In their paper, the authors refer to thermal neutrality as a condition where the subjects have a "neutral thermal sensation." In partitional calorimetry, physiologists have used for years this identical term in a totally different sense. Their definition of thermal neutrality is the condition when the body is in thermal equilibrium with its environment and when there is no regulation of body temperature by the processes of "sweating" or by "vasoconstriction." We suggest in the future that authors use "neutral thermal sensation" to distinguish between these two conditions.

For sitting-resting subjects, data available at the Pierce Laboratory for unclothed subjects indicate that the point for a neutral thermal sensation for comfort and for pleasantness falls, on an average, about the same ambient temperature (low humidity), where there is thermal (physiological) neutrality.

Using the authors' data for heat loss by radiation and convection as an index where the point of physiological neutrality would lie, one arrives at a very interesting conclusion that with increasing levels of exercise the point of neutral thermal sensation falls to a temperature level higher than what would be expected for physiological neutrality. For example, at their lowest level of exercise, the subjects reported a neutral sensation near 70 F; the corresponding point for thermal physiological neutrality, at the same level of exercise, would be at 64 F. With the middle activity level, the points for comparison would be 67 and 59 F. Further, for a neutral thermal sensation with exercise, it appears that levels of evaporative heat loss reported in Fig. 10 are roughly double the values expected when there is no thermoregulatory sweating.

After their very interesting start in an area where there is very little quantitative data on comfort and thermal sensation, I hope future studies will include actual measurement of physiological factors such as metabolic heat, skin temperature and internal body temperature.

AUTHOR McNALL: I will speak for myself as an engineer. We bow to the term physiological, or whatever we can agree on as the proper term to describe it, we will use.

JOHN WATT, Austin, Tex.: Were your subjects able to communicate while they were doing this and was there any band-wagon effect of one student influencing the votes of others?

AUTHOR McNALL: I believe you always take that chance. The indoctrination which was presented said they should not. Monitors were in the room to see that they did not discuss their thermal environment in groups. We don't believe this was a factor. We tried to control it, but you always have that possibility in group tests of this sort.

P. R. ACHENBACH, Washington, D. C.: I have had the opportunity to discuss this paper with the authors, at least one of the K. S. U. Advisory Panel and we reached a meeting of the minds on most of the comments. On the other hand, I think some of them emphasize the points that are not brought out very well. I should like to bring out a few of these.

I think it should be emphasized that the tasks that the men and women performed were similar rather than that the work rate was the same, since you find that the weight of the two genders were considerably different. The average weight for the men was 164 lb and 130 lb for the women, so that mechanical work rate would be different.

You find in comparing the data that the ratio of the metabolic rates for males and females were approximately the same as the ratio of weights for the men and women.

The curvilinear effect in Fig. 6 has already been mentioned. There is only one set of data that shows the quadratic effect and it seems desirable to repeat the tests on female subjects on this low activity to see whether this quadratic effect is real or only related to the particular subjects involved. Obviously, on any three-point curves, if any one of the three points is not representative it could change the whole pattern or straight curve of the line.

The paper discusses the number of steps that were taken to eliminate variables in making comparisons between the men and women subjects. However, there was probably an ecological relation between them. The men were five in. taller than the females, yet they were all exercised on steps nine in. in height. So there was probably a difference in mechanical advantage in walking operations between these two kinds of subjects.

The indoctrination reported in Appendix D for the subject indicates they were not given any guidance in the meaning of the terms of thermal comfort scale or variation of the thermal sensation associated with difference. Of course, the monitors had only one contact with each subject since they were all naive subjects. Apparently they were not cautioned about the possibility of using thermal comfort for fatigue and the annoying discomfort by moistening. There is possibility there was a fatigue on the part of the female at a high rate and there was significant perspiration by all the subjects in parts of the test.

I would like to question whether it is desirable to include Figs. 11 and 12 as a design at the present state of knowledge on the relation of activity level to determine comfort. The logical conclusion from these two figures is that it is unnecessary or unimportant to control the relative humidity from the range of 25 to 65% at least for the low and medium activity level.

There are other reasons, of course, that thermal comfort for control or limiting the relative humidity in working conditions. The Data Tables III, IV, and V indicate a small effect of thermal and a degree comparable to that shown in 11 or 12 of sedentary. Furthermore, the thermal control point for males is plotted on Fig. 11. The curve has a shaped position somewhat like those for female subjects. In my opinion, a vertical straight line shown for male subject at high activity does not adequately represent Table V.

In my last comment, the unexplained tables III, IV, V, and VI -- it seems to be desirable to run a limited test of trained subjects. Certainly we do not question the statistical value of a large number of untrained students to determine the difference between an individual and obvious meaningful average relationships. Nevertheless, the significance and effect of the work rate on comfort and the pressure of quadratic effects on humidity and comfort could be more accurate if additional tests of trained individuals were made. The reliability of Figs. 11 and 12 could be materially improved by these additional tests.

Thank you very much. (Applause)

AUTHOR McNALL: Yes, I certainly agree with those comments, Mr. Achenbach, and I think we should discuss them later in the committee this afternoon and see what changes need to be made.

EDGAR L. GALSON, Syracuse, N.Y.: I merely want to make the observation that for the purposes of these tests the subjects were all dressed alike; and, certainly, in many cases in ordinary office buildings, the females and males are not dressed alike, and it has been my observation that there has been a difference between males and females. This report does not show that.

AUTHOR McNALL: Yes, that is certainly true and anyone involved in this work at all knows there are about 15 or so variables that you might consider independent ones. Certain clothing is one of those and it is on the list for the future activity to see what effect clothing has.

We picked the standard and wanted to keep it out of the results of the variables. We think we picked a reasonable standard that people do wear as clothing in such conditions.

DR. FAHNESTOCK: I would like to comment on clothing. We have done a considerable amount of environmental work with females and their clothing. I was hopeful that current and future Society work would be with normally clothed subjects because we know that clothing, especially on the extremities, has a great affect on vaso-motor regulation.

I would like to emphasize that the female be clothed in clothing that is acceptable to the females who are going to occupy the air-conditioned spaces in which we are interested. The textile division in your home economics department could be of great help in selecting typical clothing. Typical shoes, instead of wool socks in place of shoes, should be used, along with typical hose. Male subjects should have their shirttails inside of their pants and be dressed like they would be in the shop or wherever they are engaged in physical activities resulting in metabolic rates similar to those under study. Our experience indicates that typical clothing details are of vital importance. It is very important to do that from our experience with clothing.

DR. McNALL: Even though Kansas State is one of the more conservative universities, both the men and women often seem to look pretty much like these pictures. (Applause)