THE EFFECT OF ENCLOSURE SURFACES, WITH TEMPERATURE SEPARATIONS RANGING TO 75F, ON THE THERMAL AND COMFORT SENSATIONS OF SEDENTARY SUBJECTS

by

RONALD EUGENE BIDDISON

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Approved by:

Major Professor

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INTRODUCTION

Comfort has been the continual goal of man since his earliest existence. Human comfort is influenced in varying degrees by a countless number of factors. The physical factors affecting human comfort include lighting, sound, smell and touch as well as the thermal environment. Although a satisfactory thermal environment does not insure comfort, its relative importance for human comfort is obvious.

In order to specify a satisfactory thermal environment it is necessary to have a basic understanding of the cause-effect relation that exists between the thermal environment and one's thermal comfort. Although the exact relation undoubtedly varies from person to person, the following concept was considered in the present study. The thermal environment stimulates the temperature receptors embedded within the human cutaneous tissue, which in turn give rise to "thermal" sensations. As a result of this physiological process a person experiences various degrees of warmth, coolness, or neutrality (neither too warm nor too cool). In addition, the effect the thermal environment causes on a person's general impression of comfort must be considered. Comfort sensations differ from thermal sensations in that they are not closely related with any distinct physiological process, but instead reflect a person's relative general satisfaction with his environment. If the thermal environment is to provide thermal comfort it is necessary that both the thermal and comfort sensations of its occupants be satisfied.

There has been considerable research in the area of thermal comfort, especially since the early 1900's. As a result of this and continuing research man is coming to better understand how the primary thermal variables, (air temperature, MRT*, relative humidity, and air movement), affect thermal comfort.

The studies of Nevins (65) and McNall _et al_. (55) have established criteria for thermally neutral conditions for people seated and engaged in various levels of activity. The findings of these studies are applicable for a uniform environment i.e. MRT equal to air temperature. However the use of heated (or cooled) panels for space heating and cooling introduces a departure from the uniform environment, namely an MRT different than air temperature. The MRT in such situations may be uniform, (all enclosure surfaces at one temperature), or more generally, asymmetric (enclosure surfaces with different temperatures). A study by McNall (55) has defined zones of thermal neutrality for the case of uniform MRT. However information concerning the asymmetric MRT is at present incomplete.

The case of an asymmetric MRT gives rise to two questions of primary importance to the environmental engineer:

1. Do the thermal sensations produced by an asymmetric MRT differ significantly from those of the uniform MRT?
2. Does an asymmetric MRT have a deleterious effect on man's comfort sensations?

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*MRT (mean radiant temperature) - that uniform temperature of a black enclosure with which an object would exchange radiant energy equal to the radiant exchange in its actual environment.

It is the purpose of this study to provide the information to answer these questions. The types of asymmetric MRT investigated were chosen to compliment and extend the works of previous investigators (56) (8) such that the results would be applicable to those situations most frequently encountered in the field.

REVIEW OF LITERATURE

As man has progressed through the years he has conintually strived to better understand how his environment could be altered to provide a greater degree of comfort. During the 18th century the discomfort of crowded rooms was felt to be primarily due to overheating, but "bad air" was held partly responsible. Lavoisier, after examining the composition of the air in occupied rooms, concluded that the excess of carbon dioxide present was largely responsible for much discomfort. However in 1883 Hermans, a German researcher, attributed the discomfort to heat and high humidity rather than poor ventilation and chemical effects.

The chilling effect of the wind had long been recognized, for as early as 1733 Arbuthnot explained that the wind caused its chilling effect by dispersing the layer of warm air that invests the body. In 1803 Sir John Leslie incorporated the chilling effect of wind as the basis of a primative anemometer.

Tredgold, 1824, is the first researcher reportedly to be concerned with the effect of radiant heat transfer. Tredgold found that a lower indoor air temperature was required for comfort in the presence of an open fire than when only the air was warmed. In 1857 the General Board of Health (England), finding cold walls as a cause of discomfort, specified as a requirement of comfort that the temperature of the walls of a room should be at least as high as the general temperature of the room.

By 1914 the importance of the four primary factors of the thermal environment (air temperature, air velocity, air moisture content, and the radiation exchange with the surrounds) had been realized. At this time Dr. Leonard Hill introduced the kata-thermometer, for the purpose of indicating the combined effects of the various thermal factors on the heat loss from the human body. The cooling rate of the heated kata-thermometer was a measure of the "cooling power" of the environment, which Hill advocated as an index of warmth in cool conditions.*

In 1894 the American Society of Heating and Ventiliating Engineers (A.S.H.V.E.)** was formed, one of its goals being expansion of the existing knowledge of the requirements for comfort. The A.S.H.V.E. Research Laboratory was established in 1919 at Pittsburg, Pennsylvania. About that time the term "comfort zone" was reportedly first introduced by Professor John Sheppard at Teacher's Normal College in Chicago.

In 1923, Houghton, and Yaglou (43, 44) published the first findings to come out of the A.S.H.V.E. laboratory at Pittsburg, Pennsylvania. Their findings established "Lines of Equal Comfort", defined "Effective Temperature" and determined the "Comfort Zone." In their experiments subjects walked from one room, controlled with respect to air temperature and humidity, to a second room. The con-

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*The preceding summary has been taken from Bedford (2) and Nevins (64), both of whom are respected researchers in the area of thermal comfort.

**A.S.H.V.E. was changed to American Society of Heating, Refrigerating, and Air Conditioning Engineers (A.S.H.R.A.E.) in 1959.

ditions of the second room were adjusted until the instantaneous evaluation of comfort sensations of the subjects were indentical with their reaction to the first room. The results were then plotted on a psychometric chart and were first known as lines of equal warmth. The effective temperature (ET) was defined as an arbitrary index which incorporates into a single value the effects of air temperature, humidity, and air velocity on the thermal sensations determined in the above experiments. The numerical value of ET was taken as that value of still saturated air which would cause equal sensations of warmth. The comfort zone was defined as including those values of ET over which 50% or more of the people were comfortable. On this basis for clothed, sedentary subjects of both sexes Houghton and Yaglou (43) found the comfort zone limits to be 62 and 69 F ET with a comfort line at 64 F ET. This comfort line corresponds to 68 F dry bulb temperature at 45% relative humidity.

In 1929 Yaglou and Drinker (77) revised the comfort chart by the addition of a summer comfort zone. The comfort chart that was published in 1929 is basically the same chart that appeared in the 1967 A.S.H.R.A.E. Handbook of Fundamentals, except that after careful analysis of the original data, the winter and summer comfort zones have been omitted. Subsequent studies by Koch and Jennings (49) and Nevins et al. (65) indicate that for extended exposure ET overestimates the effect of humidity on thermal comfort.

The definition of thermal comfort varies with individual researchers. Glickman (31) defines comfort as "a derived state of feeling based on a physiological balance of the individual to his environments wherein the stimuli are of low intensity." Leopold (52) defines comfort as the "absence of discomfort due to temperature and atomospheric effects indoors." Nevins (63) states that "criteria for thermal comfort are specifications for the indoor environment in which an arbitrary percentage of the occupants will express thermal comfort." Gagge (20) suggests that in addition to the obvious thermal sensations associated with thermal comfort, the comfort sensations of the environment should be considered. THE A.S.H.R.A.E. standard (1) defines thermal comfort as "that condition of mind which expresses satisfaction with the thermal environment."

In the early 1930's a series of investigations was initiated at the John B. Pierce Laboratory of Hygiene, New Haven, Connecticut. A relatively few number of subjects were exposed to many different thermal environments. Utilizing the technique of partitional calorimetry, the effects of humidity, air temperature, air movement, and and radiant temperature on the heat transfer from the human body were evaluated (23) (72) (73) (74). A new parameter, operative temperature, was developed by Gagge (22) at the Pierce Laboratory. Operative temperature was defined as the uniform temperature of air and surrounds with which the human body would experience heat losses equal to those of the actual environment. Recently a series of tests with subjects exposed to high-temperature sources have been conducted at the Pierce Laboratory (26) (28) (30). The operative temperature has been expanded to include thermal environments of this nature. A unique device, the R-Meter is described by Gagge (29) which directly indicates the operative temperature of its spherical sensor. The operative temperature for the human body can be determined with corrections suggested by the author (29).

The analysis of heat transfer from the human body has been the object of many additional studies. Significant contributions concerning the radiative and conductive heat losses have been made by Hardy and DuBois (34), Neilsen and Pedersen (66), and most recently Colin and Houdas (12). The effective radiation area of the human body for several body positions has been determined by Guibert and Taylor (32), Hardy and DuBois (34), and Colin and Houdas (12). Mitchell et al. (60), has reported that the emissivity of the human skin is 0.995 for both black and white skin. The evaporative (sweat) losses of thermally neutral subjects is reported by Fanger (17) to be proportional to their rate of heat production. The diffusion of water vapor through the skin has been studied by Brebner (5). Although this list is far from complete it is indicative of the research activity in this area.

A series of environmental comfort studies have been conducted at the A.S.H.R.A.E. environmental test chamber after its relocation at Kansas State University, Manhattan, Kansas. The typical procedure has been to expose a relatively large number of untrained, college age subjects to a discrete set of environments so that a meaningful statistical analysis can be performed on the subjects' responses of thermal sensation. Thermally "neutral" conditions have been established for persons engaged in several distinct levels of activity (57) (65). It was the purpose of a subsequent related study to measure these metabolic rates (58). It was at the A.S.H.R.A.E. laboratory that Fanger (17) compiled the physiological data that serves as the basis of the "Basic Comfort Equation." Fanger's comfort equation includes all the uniform environmental factors which affect heat transfer from the human body. With additional refinement it will be a valuable tool for specifying conditions of thermal neutrality. In a recent study conducted by McNall et al. (55) the relative influence of air temperature was found to be 1.4 times as "important" as mean radiant temperature for the thermal comfort of sedentary subjects. A "Thermally Neutral Zone" was developed that included combinations of air temperature and mean radiant temperature that would predictably elicit thermal sensations of "neutral."

The use of radiant panels for indoor heating or cooling perforces the exposure of the occupants to an asymmetric radiant field. If the asymmetry is too severe, even the thermally "neutral" occupants may experience noticeable discomfort. Fanger (17) states that the satisfaction of his comfort equation is only a necessary, not a sufficient, condition for thermal comfort in environments of this nature. Chrenko (8) (9) has investigated the effects of radiant panels on the subjective impressions of "freshness" and "pleasantness." Chrenko (8) reported that persons found significant discomfort from exposure to heated panels when the mean radiant temperature at head level was 4 F higher than the balance of the enclosure surface temperatures. However the comfort response of subjects exposed to enclosure surfaces separated 12 F was found by McNall et al. (56) to not be significantly different than the comfort response of subjects exposed to uniform enclosure temperatures.

Kaletzky (47) and Morse (61) have found that subjects cooled by exposure to cool panels in a hot humid environment did not find the environment acceptable. Bøje _et al_. (4) reports that repeated exposure to cold panels can produce noteable stiffness and soreness of exposed tissue.

In view of the somewhat incomplete and contradictory conclusions on the effects of an asymmetric radiant field on human comfort, it was felt to be of practical value to conduct further research in this area. It is the purpose of the present study to simulate the types of asymmetric radiant fields that would be of greatest practical value to the environmental engineer and determine their effect on both the thermal and comfort sensations of the participating subjects.

METHODS

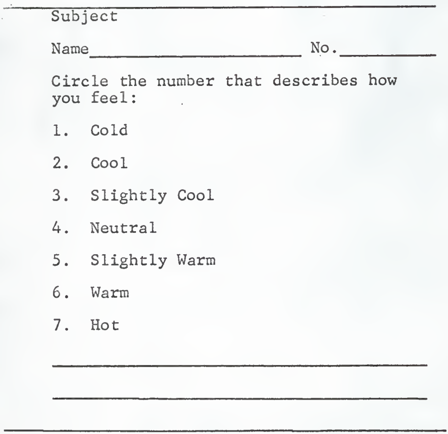
EXPERIMENTAL DESIGN

It was the purpose of this study to determine the effect of an asymmetric MRT on the thermal and comfort sensations of sedentary subjects. The ballot used in obtaining the subjects' thermal sensations is shown in Figure (1). This ballot consists of seven subjective responses which the subject may use to describe his thermal sensation at the time of voting. With the comfort ballot, Figure (2), the subject was able to describe his comfort sensations, at the time of voting, by one of the five responses listed. Both ballots have been used in previous studies (55) (56). The ballots were essentially given in pairs, at predetermined intervals during testing. The exact procedure for ballot distribution and collection is described in Procedure, page 31. Each pair of thermal and comfort ballots was considered to be a single vote describing the subjects' thermal comfort at the time of voting.

The types of asymmetric MRT most generally encountered are those where spaces are heated or cooled by either wall or ceiling panels. For the results of this study to be of practical value it was obvious that several distinct series of tests were needed.

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 surface of the test chamber. The experimental combinations of MRT and air temperature investigated are shown in Figure 3 and Table (1) lists



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

____

____

Figure 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

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Figure 2. The comfort ballot used to evaluate the comfort sensation response of the subjects

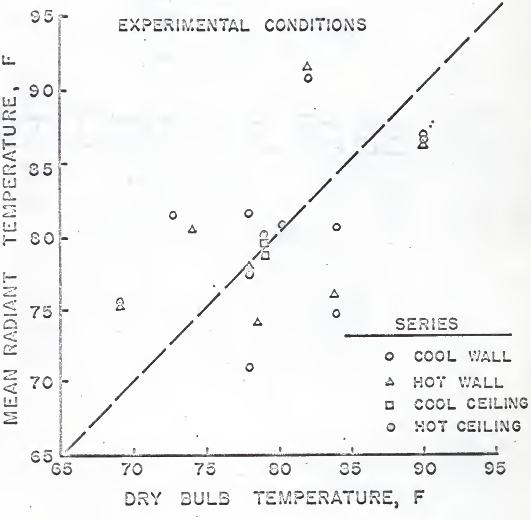

Figure 3. The Experimental Conditions of MRT and Air Dry Bulb Temperature Investigated

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)	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

Control Series		
Cond. No.	Air Temp. (F)	Chamber Surface Temp (F)
1	78	78
2	78	78
3	78	78

Hot Wall Series			
Cond. No.	Air Temp. (F)	Chamber Surface Temp.	
		West Wall (F)	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)	Balance (F)
1	79	52	80
2	79	51	80

Hot Ceiling Series			
Cond. No.	Air Temp. (F)	Chamber Surface Temp.	
		Ceiling (F)	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 the air and chamber surface temperatures for each Cool Wall tests. 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. The work of McNall _et al_. (56) reports that this is a valid assumption. Figure (A-1), Appendix (A), shows a plan view of the seating arrangement used in this series. The photograph of Figure (4) pictures a group of subjects during testing. A shape factor of 0.20, subject to cooled wall, was considered to be about the most extreme exposure one would encounter in typical situations. A Honeywell two-sphere radiometer (69), described later, used to measure MRT, was also placed so that its shape factor to the long wall was 0.20.

A linear statistical model was employed to relate the thermal sensation responses of the subjects to the independent variables considered. The model was:

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

where:

Y = estimated thermal sensations vote

$\overline{Y}$ = mean thermal sensation vote

b_1, b_2 = partial regression coefficients

t_a = the indenpendent variable representing dry bulb air temperature ($\overline{t}_a$ = mean t_a)

t_{mrt} = the independent variable representing the MRT as measured by the Honeywell radiometer ($\overline{t}_{mrt}$ = mean t_{mrt})

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

An F test, described by Chow (7), was then used to determine if the resultant regression plane derived for the Cool Wall series (asymmetric MRT) and the regression plane reported by McNall et al. (55) derived from uniform MRT data actually represent the same regression plane. A non-significant value of F lead to acceptance of the null hypotheses, that both groups of thermal sensation votes belong to the same regression plane, and rejection of the alternative hypothesis, that the two equations represent different regression planes. Availability of the original data of McNall et al. (55) made possible this comparison of regression planes.

As stated in the introduction it was a primary objective of this study to determine the effect of an asymmetric MRT on subject comfort. Previous studies (20) (55) (56) have shown that any deviation from thermal neutrality increases the probability that a subject will experience some degree of discomfort. It was felt that only those comfort votes accompanied by a thermal sensation of "neutral" would be meaningful in determining what effect, if any, an asymmetric MRT has on subject comfort. The comfort votes that met this requirement were than classified either "comfortable" (vote of A) or "uncomfortable" (vote of B, C, D, or E). This same criteria and classification of votes was performed on the thermal comfort votes of subjects in an environment with uniform chamber surface temperatures equal to air temperature. It was felt that a uniform environment would cause minimal subject discomfort for the testing procedure and would serve as a basis for evaluation of the effect of asymmetric MRT on subject comfort. The two-way classification of the comfort votes for a given condition of asymmetric

MRT and of the comfort votes for the uniform environment form a 2 X 2 contingency table. A chi-square test was then used to determine if the two environments had significantly different probabilities of producing subject discomfort.

Seven combinations of asymmetric MRT and air temperature were selected for experimental points. The results of McNall et al. (55) were consulted to choose combinations that would on the average elicit thermal sensation votes of 3-5. Based on the results of previous studies (55) (56) (57) an estimate of the variation of thermal sensation responses could be predicted. It was felt that exposing ten subjects to each of seven experimental points would provide sufficient data so the previously described comparisons could be made. Thirty additional subjects were eventually used in the Cool Wall series in order to better understand what was originally regarded as unexplainable results.

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 Figure (3) and Table (1) lists the air and chamber surface temperatures for each Hot Wall test.

A slightly modified comfort ballot, Figure (5), was used during the final three votes of each test of the Hot Wall series. If a subject circled a comfort response other than A, "comfortable," 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)____________________________

____

____

Figure 5. The modified comfort ballot used to determine the cause of any subject discomfort.

he was instructed to circle the reason(s) which contributed to his discomfort. Four possible reasons were listed, with the subject instructed to describe the cause of his discomfort if it was different than those listed. It was hoped that the use of this ballot would determine the cause of any discomfort.

Cool and Hot Ceiling Series

In this series of tests subjects were exposed to a heated or cooled ceiling. The shape factor for all subjects to the temperature controlled panels of the ceiling was approximately 0.12. Figure (A-2), Appendix (A), shows a plan view of the subjects' seating arrangement in the chamber.

Only the comfort sensations were analyzed in this series, although both ballots were necessarily used. In order to obtain an adequate number of comfort votes for the previously described chi-square test, combinations of MRT and air temperature were chosen that were predicted to elicit thermal sensations of "neutral." The experimental conditions of the Cool and Hot Ceiling series are shown in Figure (3) and the air and chamber surface temperatures for each ceiling test listed in Table (1).

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 <u>et al</u>. (65), so that a predicted maximum of thermal comfort votes with "neutral" thermal sensations would be obtained. The comfort sensations of votes meeting this criteria were then used in the chi-square test to determine if the asymmetric MRT in question produces a statistically significantly higher probability of subject discomfort than does a uniform environment. Three tests, with twelve subjects each, were conducted.

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). This was done to minimize variation in evaporative heat losses by diffusion of moisture from the body and latent respiratory heat losses. For a give metabolic rate both are reported (6) (54) to be dependent upon the water vapor pressure gradient from the skin to the air. 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 to prevent formation of moisture on cooled chamber surfaces. The finding of Nevins et. al. (65) show air moisture content for the conditions of this study has 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 f.p.m., 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 standard sound-level meter. Insofar as possible these values were held constant throughout all testing. MRT was measured with the Honeywell two-sphere radiometer (69). It should be reemphasized that the MRT indicated by the Honeywell radiometer represents an integreated average of enclosure surface temperatures as "seen" by the radiometer. Thus a highly asymmetric radiant field can be represented by a single value of MRT.

FACILITIES

This research project was carried out at the Institute of Environmental Research, Department of Mechanical Engineering, Kansas State University, Manhattan, Kansas.

All testing was performed in the Environmental Test Chamber located at the Institute. This facility which was originally located at the ASHRAE Laboratory at Cleveland, Ohio, was moved to Kansas State University and placed in operation in 1963. The chamber is 12 feet wide, 24 feet long, and has a ceiling of adjustable height. For all tests of this study the ceiling height was maintained at eight feet. A floor plan view of this chamber and adjoining facilities is shown in Figure (6).

All interior surfaces of the test chamber are aluminum panels. Attached to the exterior of these panels is copper tubing through which heated or chilled water may be circulated.

By controlling the temperature of the circulating water, panel surface temperatures can be maintained at any temperature within the range of 40-150 F. Four separate circuits of tubing allow the ceiling, floor, and walls of the chamber, or parts thereof, to be controlled independently of one another.

Conditioned air enters the test chamber through perforated inlet strips located between the ceiling panels and exits through concealed slots around the perimeter of the floor. Separate heating and cooling coils located in the main ductwork are capable of maintaining chamber air temperatures of 40-150 F. A capillary

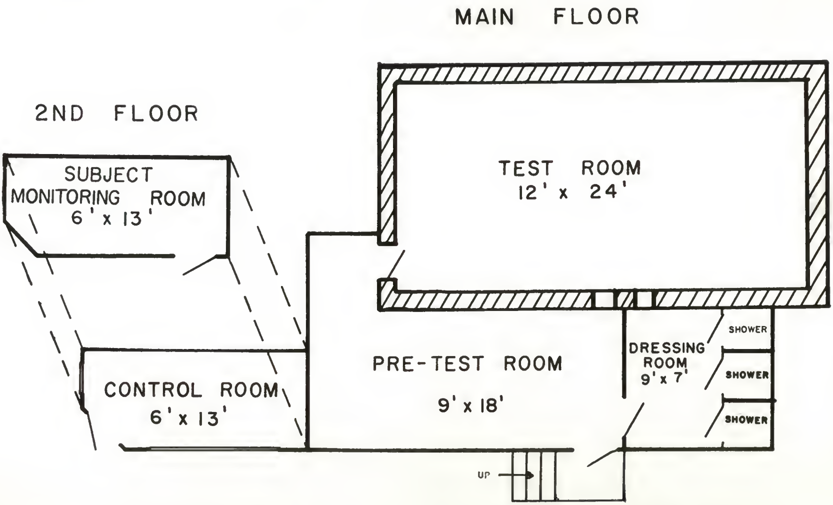

Figure 6. Floor Plan of the KSU-ASHRAE Environmental Laboratory Facility.

air washer, for humidification, and a sorbent dehumidifier are capable of maintaining the test chamber at relative humidities of 10% to 95%.

A 15 hp compressor supplies an insulated 500 gallon chilled liquid supply tank. The chilled liquid (water) is circulated through the tank and heat exchanger by a pump which also provides adequate mixing in the tank. The temperature of the supply tank liquid is controlled by a pnuematic thermostat. A smaller 220 gallon insulated hot-liquid storage tank is provided and maintained with steam supplied by the University boilers. Utilizing a system of pnuematically controlled mixing valves, liquid at the desired temperatures can be circulated through the four independent panel circuits. The entire system is remotely and automatically controlled at the control room located adjacent to the pre-test room (Figure 7). Both electronic and pneumatic controls are used in maintaining the test chamber at the selected conditions. Both the air and liquid circuits are represented schematically on the walls of the control room. Lights located on this display indicate the equipment that is in current use.

Test chamber air and wet bulb temperature are measured with a motorized psychrometer and can be monitored continuously in the control room. An indicating potentiometer is used to measure chamber surface temperatures plus other air and liquid temperatures in the control circuits. A physiological monitoring room is located above the control room. Instrumentation for monitoring subject body temperatures, and heart rate is available. Operant condition-

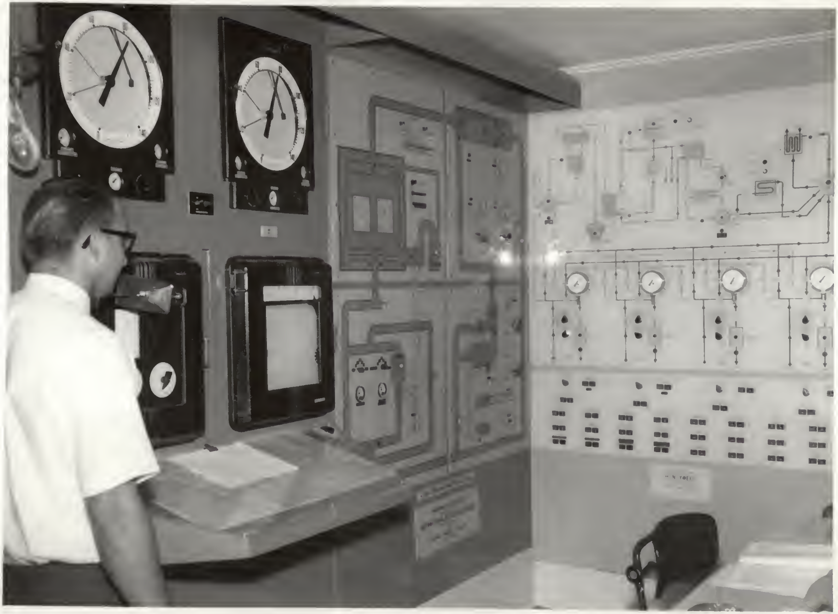

Figure 7. The Control Room of the KSU-ASHRAE Environmental Laboratory Facility.

ing and programming equipment is also located in this room.

A more detailed description of the original facility in Cleveland including construction, design, piping circuits, electronic controls, etc., is available from Tasker, (70). A description of the present facility was included in the recent paper by Nevins, et al. (65).

MRT was measured in the test chamber by means of a Honeywell 2-sphere radiometer (69). 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 non-directional mean radiant temperature, MRT, from convenient operating curves accompanying the radiometer. The average error has been measured as less than .4 F (48). The radiometer was placed in a position similar to that of one of the subjects. Its location for the Cool and Hot Wall series, and both Ceiling series are shown in Figures (A-1) and (A-2), Appendix (A), respectively.

PROCEDURE

All tests were conducted in the afternoon or evening during the period January 1967 to October 1968 inclusive. Subjects were selected from college age applicants and were randomly assigned to a testing session. The subjects were naive in the practice of voting on the thermal sensation and comfort sensations that were employed in the tests. It was felt that these interpretations of the various responses on ballots were more representative of the general population than subjects which had been specially trained. No subject was allowed to participate in more than one test of any series. A registered nurse and an assistant served as monitors for each testing session. They recorded data taken in both the pre-test room and the test chamber.

The subjects were given cotton twill uniforms to wear during the testing. The underwear consisted of brassieres and underpants for the women and shorts for the men. The subjects wore cotton sweat socks, but no shoes. The insulation value for the complete ensemble was approximately 0.6 clo. Figure (4) shows the subjects dressed in this fashion.

The subjects remained in the pre-test room approximately one-half hour before entering the test chamber. During this time the nurse obtained each subject's height, clothed weight, oral temperature and pulse rate. No subject with an oral temperature greater than 99 F was allowed to participate in the testing.

A summary of physical data for the subjects used in testing is shown in Table 2. Additional information was taken (see Appendix E) which might aid in explaining unusual subject response, i.e. amount of alchol consumed in the last 24 hours, amount of sleep and work etc. Temperature of the pre-test room was maintained at approximately 78 F and 45% RH for all tests. Just prior to entering the test chamber the subjects received an oral indoctorination explaining the purpose and procedure of the test (see Appendix B). While in the pre-test room the nurse randomly assigned each of the subjects to one of the numbered seating positions in the test chamber.

Table 2

Physical Characteristics of Subjects Participating in the Cool and Hot Wall Series

Sex	No. of Subjs.	Age (yr)	Height (in)	Weight (lb) (nude)	Surface Area
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

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* Mean

** Standard deviation

After pre-test preparations were completed the subjects were taken into the test chamber adjacent to the pre-test room. Each subject was seated in the class-room chair to which he had been assigned. Two 1-foot square, two inch thick pads were provided to each subject; one to sit on, the other to place his feet on preventing direct contact of the subject's stocking feet and the test room floor.

All testing sessions were of three hours duration. The subjects were allowed to study, read or engage in limited conversation during testing. However the subjects were instructed not to discuss their votes so that independent opinions of thermal comfort would be obtained. The subjects were allowed to drink the supplied tap water ad lib, and the amount consumed by each subject was recorded. Care was taken to prevent any of the subjects from sleeping during testing.

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.

After the final votes had been collected the subjects returned to the pre-test room. After their final weight had been taken the subjects were paid and allowed to leave.

RESULTS

The purpose of this study was to determine the effect of an asymmetric MRT on the thermal and comfort sensations of sedentary subjects. 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. Figure (8) 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. Figure (8) 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 Figure (8) 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.

It was found that the response of comfort sensation of thermally "neutral" subjects participating the Cool Wall, Cool Ceiling and Hot Ceiling series was not significantly different than that of the thermally "neutral" subjects of the Control series. However, the thermally "neutral" subjects participating in the Hot Wall series displayed a statistically significantly lower probability of feeling "comfortable" than the thermally "neutral" subjects of the Control series. These findings are summarized in Table (3).

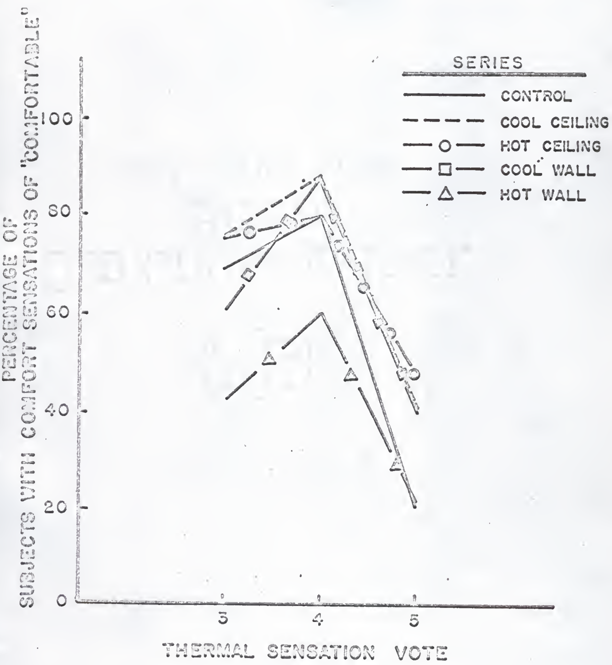

Figure 8. The Distribution of Comfort Sensation Votes of "Comfortable" within the Thermal Sensation Votes for Sedentary Subjects of All Series Conducted

Table 3

Comfort Sensation Response of Thermally "Neutral" Subjects

Series	Comfortable		Not Comfortable (B,C,D, or E)		Total
	No. of Votes	%	No. of Votes	%	Votes
Control	89	79.5	23	20.5	109
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
* $p < .10$
** $p < .05$
*** $p < .01$

The modified comfort ballot, Figure (5), used for the final three votes of thermal comfort during the Hot Wall series, showed that 60% of the thermally "neutral" subjects that voted "not comfortable" indicated that the sole cause of their discomfort was due to one side of their body feeling warmer than the other. Another 15% felt that uneven body surface temperature was a contributing factor to their discomfort, while 25% gave a reason other than uneven body temperature. Table (4) summarized these findings. Although these findings are based on a relatively small number of votes, it appears that uneven body temperature was a significant cause of the discomfort of the thermally "neutral" subjects of the Hot Wall series.

TABLE (4)

Results of the Modified Comfort Ballot for Thermally "Neutral" Subjects Participating in the Hot Wall Series

No. of Votes With Thermal Sensations of "Neutral"	Votes with Comfort Sensation Response of "Not Comfortable" (B,C,D, or E)		Indicated Cause of Discomfort		
	No.	%	3* Alone	3 Contributing	Other Than 3
34	20	58.8	12	3	5

* Response 3 = "One side of my body feels warmer than the other (or cooler)."

Table (4) indicates that only 41.2% of the thermally "neutral" subjects voted comfortable, a significantly lower percentage than shown in Table (3) for the Hot Wall series. It was felt that the modified comfort ballot, Figure (5), may have increased the probability of 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.

A second major purpose of this study was to determine if the thermal sensations evoked by a given condition of asymmetric MRT was significantly different than the relation reported by McNall, et al. (55) for a uniform MRT. The regression equations relating thermal sensation response with the independent variables of air temperature and MRT, for the Cool Wall and Hot Wall series are listed below. In order to determine if these regression planes were significantly different from those developed for a uniform MRT it was necessary to derive the regression equations based on pooled data. These resultant regression equations are also listed. Table (5) summarizes the supportive statistics associated with following regression equations.

Uniform MRT

$$Y_{m+f} = 4.00 + 0.111(t_a - 78.88) + 0.077(t_{mrt} - 81.01) \qquad (1)$$
$N = 160$

$$Y_m = 4.03 + 0.099(t_a - 78.88) + 0.066(t_{mrt} - 81.01) \qquad (2)$$
$N = 80$

$$Y_f = 3.99 + 0.122(t_a - 78.88) + 0.088(t_{mrt} - 81.01) \qquad (3)$$
$N = 80$

where:

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

Y_m = estimated thermal sensation vote of college-age males for a given combination of air temperature and MRT

Y_f = estimated thermal sensation vote of college-age 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

Cool Wall Series

$$Y_{m+f} = 3.97 + 0.121(t_a - 80.69) + 0.056(t_{mrt} - 80.77) \qquad (4)$$
$N = 100$

$$Y_m = 3.90 + 0.076(t_a - 80.77) + 0.040(t_{mrt} - 80.83) \qquad (5)$$
$N = 50$

$$Y_f = 4.03 + 0.165(t_a - 80.61) + 0.072(t_{mrt} - 80.70) \qquad (6)$$
$N = 50$

Hot Wall Series

$$Y_{m+f} = 4.49 + 0.124(t_a-79.53) + 0.035(t_{mrt}-79.94) \quad N = 70 \tag{7}$$

$$Y_m = 4.44 + 0.054(t_a-79.49) + 0.058(t_{mrt}-79.97) \quad N = 35 \tag{8}$$

$$Y_f = 4.54 + 0.194(t_a-79.57) + 0.009(t_{mrt}-79.90) \quad N = 35 \tag{9}$$

Uniform MRT and Cool Wall Series

$$Y_{m+f} = 3.99 + 0.110(t_a-79.57) + 0.073(t_{mrt}-80.92) \quad N = 260 \tag{10}$$

$$Y_m = 3.98 + 0.085(t_a-79.60) + 0.058(t_{mrt}-80.94) \quad N = 130 \tag{11}$$

$$Y_f = 4.01 + 0.135(t_a-79.54) + 0.087(t_{mrt}-80.89) \quad N = 130 \tag{12}$$

Uniform MRT and Hot Wall Series

$$Y_{m+f} = 4.15 + 0.115(t_a-79.07) + 0.064(t_{mrt}-80.68) \quad N = 230 \tag{13}$$

$$Y_m = 4.15 + 0.088(t_a-79.06) + 0.058(t_{mrt}-80.70) \quad N = 115 \tag{14}$$

$$Y_f = 4.16 + 0.141(t_a-79.09) + 0.071(t_{mrt}-80.67) \quad N = 115 \tag{15}$$

Table 5

Regression Equation Values Used in Predicting the Thermal Sensation of Sedentary Subjects and Supportive Statistics

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

Series	Sex	Eq.	$\overline{Y}$	$\overline{t}_a$	$\overline{t}_{mrt}$	b_1	t_{b_1}	s_{b_1}	b_2	t_{b_2}	s_{b_2}	R^2	$s_{y \cdot x}$	b_1/b_2
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
	M	2	4.03	78.88	81.01	0.099	8.16^{***}	0.012	0.066	5.67^{***}	0.012	0.629	0.651	1.51
	F	3	3.99	78.88	81.01	0.122	8.61^{***}	0.014	0.088	6.53^{***}	0.014	0.688	0.761	1.37
Cool Wall	M+F	4	3.97	80.69	80.77	0.121	8.87^{***}	0.014	0.056	3.73^{***}	0.015	0.637	0.747	2.16
	M	5	3.90	80.77	80.83	0.076	4.90^{***}	0.015	0.040	2.34^{*}	0.017	0.541	0.588	2.11
	F	6	4.03	80.61	80.70	0.165	8.72^{***}	0.019	0.072	3.44^{**}	0.021	0.773	0.739	2.32
Hot Wall	M+F	7	4.49	79.53	79.94	0.124	6.36^{***}	0.020	0.035	1.68	0.021	0.521	0.857	-
	M	8	4.44	79.49	79.97	0.054	2.21^{*}	0.024	0.058	2.39^{*}	0.024	0.398	0.764	0.93
	F	9	4.54	79.57	79.90	0.194	7.49^{***}	0.026	0.009	0.29	0.030	0.715	0.800	-
Uniform MRT and Cool Wall	M+F	10	3.99	79.57	80.92	0.110	14.43^{***}	0.008	0.073	9.38^{***}	0.008	0.630	0.731	1.51
	M	11	3.98	79.60	80.94	0.085	8.82^{***}	0.010	0.058	5.99^{***}	0.010	0.570	0.648	1.47
	F	12	4.01	79.54	80.89	0.135	12.13^{***}	0.011	0.087	7.67^{***}	0.011	0.710	0.758	1.55

(cont.)

Table 5 Concluded

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

Series	Sex	Eq.	$\overline{Y}$	$\overline{t}_a$	$\overline{t}_{mrt}$	b_1	t_{b_1}	s_{b_1}	b_2	t_{b_2}	s_{b_2}	R^2	$s_{y \cdot x}$	b_1/b_2
Uniform MRT and Hot Wall	M+F	13	4.15	79.07	80.68	0.115	12.85^{***}	0.009	0.064	7.32^{***}	0.009	0.577	0.792	1.80
	M	14	4.15	79.06	80.70	0.088	7.72^{***}	0.011	0.058	5.27^{***}	0.011	0.530	0.719	1.51
	F	15	4.16	79.09	80.67	0.141	10.63^{***}	0.013	0.071	5.36^{***}	0.013	0.638	0.831	1.98

R^2 = Square of the Multiple Linear Correlation Coefficient
s_{b_i} = Standard Error of b_i
t_{b_i} = t Ratio = $\frac{b_i}{s_{b_i}}$

$s_{y \cdot x}$ = Standard Error of Y for Given Values of t_a and t_{mrt}

Y = Thermal Sensation, ($\overline{Y}$ = mean Y)
t_a = Air Dry Bulb Temperature, ($\overline{t}_a$ = mean t_a)
t_{mrt} = Mean Radiant Temperature, ($\overline{t}_{mrt}$ = t_{mrt})
* = Significant at the 5% Probability Level
** = Significant at the 1% Probability Level
*** = Significant at the o.1% Probability Level

The regression analyses were performed on the average of the votes of thermal sensation for each subject during the last hour of exposure. This averaged vote was felt to be a better indication of a subject's evaluation of his thermal sensation than any single response. Previous studies (56) (58) indicated that equilibrium is reached before the third hour.

An analysis of variance was performed on the thermal sensations of subjects of the Cool Wall and Hot Wall series. The results, summarized in Appendix C, show that the thermal sensation responses were independent of seating position for both series.

Figure (9) shows lines representing predicted thermal sensations of 4, "neutral," for the different test series superimposed on the "Thermally Neutral Zone" proposed by McNall, <u>et al</u>. (55). The results are based on the regression equations developed for males and females combined.

The regression equations of Table (5) 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 although mean MRT's and air temperatures were nearly equal for both tests.
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 fe-

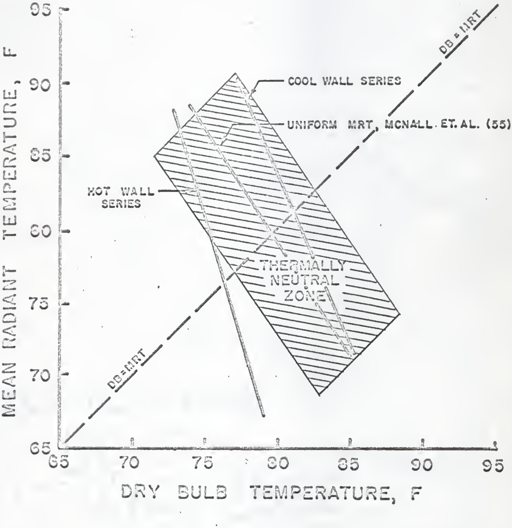

Figure 9. Lines of Predicted Thermal "Neutrality" for the Males and Females of the Cool and Hot Wall Series and the Uniform MRT Series

males 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 Figure (9) since it was felt further testing would expose a significant effect of MRT on thermal sensation.

3. In general, the ratio of the coefficient of the independent variable air temperature to the coefficient of MRT of the regression equations was higher for both the Cool Wall series and Hot Wall series than for the Uniform MRT.
4. 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.
5. 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.

6. All regression equations for predicting the thermal sensation response of females displayed a larger correlation coefficient than for the males; however, the standard error of the predicted thermal sensation was always greater for the females than the males.

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 (6).

The results of Table (6) 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 a uniform MRT. Also, the regression equations for males and females were found to be significantly different except in the case of a uniform MRT.

Table 6

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
Regression Equations Tested for Equality	**Series**	**F**	**Decision**
Males and Females	Uniform MRT	1.45	Accept H_o
	Cool Wall	9.07^{***}	Reject H_o
	Hot Wall	5.50^{***}	Reject H_o

* = Significant at the 5% probability level
** = Significant at the 1% probability level
*** = Significant at the 0.5% probability level

DISCUSSION

The energy balance for a person which describes the processes of energy production, storage, and transfer may be represented by the following equation:

$$M = E \pm R \pm C_V \pm C_D \pm S \pm W \tag{16}$$

where:

M = Rate of internal heat production

E = Rate of evaporative heat loss

R = Rate of radiative heat loss or gain

C_V = Rate of convective heat loss or gain

C_D = Rate of conductive heat loss or gain

S = Storage Rate, change in internal energy

W = Rate of external mechanical work

All terms are considered to be per unit DuBois surface area of the body.

The subjects for all tests series were sedentary, therefore, the rate of energy production, M, can be taken as constant. The evaporative heat loss, E, consists of:

1. Insensible Perspiration; Evaporation of water from the respiratory tract plus the diffusion of water vapor through the skin.
2. Sensible Perspiration; Sweat secretion from the sweat glands.

Of these, only sensible perspiration is under the thermoregulatory control of the human body. For sedentary subjects near thermally "neutral" conditions regulatory sweating is assumed equal to zero. Insensible perspiration by diffusion is reported by Brebner (5) to be proportional to the difference between the saturated water vapor pressure at the skin temperature and the partial pressure of water vapor of the air. The evaporation of water from the respiratory tract is reported by Fanger (17) to be a function of energy production rate, M, and the water vapor partial pressure of air. Since the water vapor partial pressure of air was maintained essentially constant for all tests and energy production, M, was constant, the insensible perspiration and hence total evaporative loss, E, of equation (16) can be regarded as constant for both the Cool and Hot Wall series.

For a sedentary subject in an environment near thermally "neutral" conditions the rate of storage, S, is essentially zero after two hours of exposure. Also the heat transferred by conduction is generally assumed zero because of the relatively small area of the body in direct contact with other surfaces and the typically low conductivities of such surfaces. Rearranging, the simplified form of equation (16) applicable for the conditions of testing becomes:

$$M - E = \pm R \pm C_V \qquad (17)$$

Based on the foregoing assumptions the left-hand side of equation (17) can be taken as constant for the subjects of this study.

The radiative energy exchange is represented by:

$$R = f_r f_{cl} e \sigma \left[(t_{cl} + 460)^4 - (t_{mrt} + 460)^4 \right] \qquad (18)$$

where:

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

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

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

σ = the Stephan-Boltzmann constant (BTU/hr-ft^2-R^4)

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

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

The linear coefficient of radiation heat exchange is defined by:

$$R = f_{cl} f_r h_r (t_{cl} - t_{mrt}) \qquad (\text{BTU/hr-ft}^2) \qquad (19)$$

where:

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

Although h_r is only an approximation, for the range of conditions investigated the error incurred by its use is small.

The convective heat transfer is given by:

$$Cv = f_{cl} h_c (t_{cl} - t_a) \qquad (\text{BTU/hr-ft}^2) \qquad (20)$$

where:

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

t_a = the air dry bulb temperature (F)

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

$$R + C_V = \frac{(\overline{t}_s - t_{cl})}{.88\ I_{cl}} \tag{21}$$

where:

$\overline{t}_s$ = average skin temperature (F)

I_{cl} = total resistance to heat transfer from the skin to the outer surface of the clothed body (clo)

Fanger (17) has found that for thermally "neutral" subjects, $\overline{t}_s$, the average skin temperature, is a function of metabolic rate alone, hence constant for sedentary subjects.

Substituting for R and C_V, equation (17) can now be written as:

$$M - E = f_r f_{cl} h_r (t_{cl} - t_{mrt}) + f_{cl} h_c (t_{cl} - t_a) \tag{22}$$

(BTU/hr-ft^2)

If Fanger's (17) assumption, that the average skin temperature of thermally "neutral" subjects is a function of metabolic rate alone, is valid, then the relation of air temperature and MRT necessary for thermal "neutrality" can be obtained from equation (22). From equation (21) for constant $R + C_V$, necessary to balance equation (22), t_{cl} is seen to be constant for constant $\overline{t}_s$. Differentiation of (22) yeilds:

$$\frac{dt_{mrt}}{dt_a} = - \frac{h_c}{f_r h_r} \tag{23}$$

Since the slope of the functional relation of air temperature and MRT necessary for thermal "neutrality" is constant, the following form is allowed:

$$\frac{\Delta t_{mrt}}{\Delta t_a} = -\frac{h_c}{f_r h_r} \qquad (24)$$

That is to say if the air temperature were elevated 1 F then a corresponding reduction in MRT by an amount $(h_c/f_r h_r)$F would be required to keep a person in thermal "neutrality". The validity of assuming a person's thermal sensations can be predicted on the basis of the foregoing energy balance analysis can be determined from the statistical analysis performed on the actual responses of thermal sensations obtained from the subjects during testing. The statistical model employed was of the form:

$$Y = \overline{Y} + b_1\,(t_a - \overline{t}_a) + b_2(t_{mrt} - \overline{t}_{mrt}) \qquad (25)$$

For the conditions of MRT and air temperature, which would predictably evoke equal responses of thermal sensation, the two are related by:

$$\frac{\Delta t_{mrt}}{\Delta t_a} = \frac{-b_1}{b_2} \qquad (26)$$

That is to say, a person in a given environment would predictably experience no change in thermal sensation if an elevation of 1 F were accompanied by a simultaneous reduction in MRT of (b_1/b_2)F. Table (5) summarizes the values of b_1/b_2 for the Cool and Hot Wall experimental series as well as for the Uniform MRT results reported by McNall, <u>et al</u>. (55).

It is necessary to determine a representative value of $h_c/f_r h_r$ for the conditions encountered during testing. h_r is determined by the following:

$$h_r = e\sigma \left[\frac{(t_{cl} + 460)^4 - (t_{mrt} + 460)^4}{(t_{cl} - t_{mrt})} \right] \qquad (27)$$

By using values of 86 F and 80 F for t_{cl} and MRT respectively, with the emissivity of the outer surface of the clothed body taken as 0.95, the numerical value of h_r was found to be:

$$h_r = \frac{(0.95)(0.1714 \quad 10^{-8}) \left[(86+460)^4 - (80+460)^4\right]}{(86 - 80)} = 1.04$$

For the range of MRT investigated the maximum error incurred in using the linear radiative heat transfer coefficient is approximately 3% (See Appendix E).

The value of f_r, the ratio of the effective radiative area to the nude surface area is a function of body position and clothing ensemble. Winslow, Herrington and Gagge (72), using a heat balance method, report values of f_r ranging 0.7 to 0.74 for nude, semireclining subjects. Guibert and Taylor (32), employing a photographic method, report a value of 0.7 for seated, nude subjects. Neilsen and Pederson (66) found f_r to be 0.6 for seated clothed subjects. Because of the close similarity of subject's position and attire of the present study and that of Neilsen and Pederson (66) the value of 0.6 was taken for f_r, with the resultant numerical product of f_r and h_r being:

$$f_r h_r = 0.624 \qquad (\mathrm{BTU/hr\text{-}ft^2\text{-}F})$$

There have been several studies to evaluate the coefficient of convective heat transfer, h_c. Winslow, Gagge, and Herrington

(72) report the following formula for h_c:

$$h_c = 0.152\ v^{.5} \qquad (\mathrm{BTU/hr\text{-}ft^2\text{-}F}) \qquad (28)$$

where:

v = air velocity, fpm

In a recent study by Colin and Houdas (12), the following formula is recommended:

$$h_c = 0.472 + 0.045\ v^{.67} \qquad (\mathrm{BTU/hr\text{-}ft^2\text{-}F}) \qquad (29)$$

This formula accounts for free convection as well as forced convection since at low air velocities $h_c \cong 0.472$. For free convection h_c is proportional to the temperature difference $t_{cl} - t_a$, which is probably larger for the nude experimental subjects used by Colin and Houdas (26) than the clothed subjects of the present study. Evaluation of h_c by equations (28) and (29), with air velocity taken as 25 f.p.m., results in numerical values of 0.760 and 0.860 respectively. Using the average, h_c is taken as:

$$h_c = 0.810 \qquad (\mathrm{BTU/hr\text{-}ft^2\text{-}F})$$

The ratio, $h_c/f_r h_r$, representative for the conditions of the present study is found to be:

$$h_c/f_r h_r = 1.30$$

It was found that the regression planes relating thermal sensations with air temperature for the males and for the females of the Uniform MRT were not significantly different, hence the regression plane described by equation (1) for males and females combined is also applicable for either sex alone. The ratio of b_1/b_2 of 1.43 is in relatively good agreement with the value assumed for $h_c/f_r h_r$, especially considering the high variability generally associated with the subjective assessment of one's thermal sensation. However based on the value of b_1/b_2 it appears that the value of h_c, relative to $f_r h_r$, may have been underestimated.

The results of the regression analysis performed on thermal sensations of subjects participating in the Cool Wall series show a value of b_1/b_2 of about 2.2. Although this ratio is higher than that observed for the Uniform MRT series, the regression planes for males and females combined of the two series were found to be not significantly different. Therefore, Equation (10) is applicable, with b_1/b_2 equal to 1.51 which, again, shows relatively good agreement with the value taken for $h_c/f_r h_r$.

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", Figure (8), proposed by McNall et al. (55), is applicable for persons exposed with radiation shape factors of 0.20 to cool walls at 50 F. It can be assumed that the same zone would be applicable for less extreme combinations of radiation shape factors and cool wall temperatures.

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, and females were all found to be significantly different from the corresponding planes of the Uniform MRT series. As illustrated in

Figure (8) 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. (55). The thermal sensations of the subjects of the Hot Wall series were obviously 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 equal, but less asymmetric, MRT 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. (58). Since the metabolic rates of males and females are different, each sex was considered separately. The regression equation reported by Fanger (17) was used to determine the average skin temperature, $\overline{t}_s$, 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 (5). By setting equations (21) and (22) equal, the average outer surface clothing temperature could be found. $R + C_V$ was then calculated from equation (21). 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.

From Table (7) 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 (10), which shows the mean thermal sensation with exposure time, indicates that the subjects of the Hot Wall series had attained some degree of thermal equilibrium 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 (17) does not hold for thermal environments of this nature.

Table 7

Metabloic 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

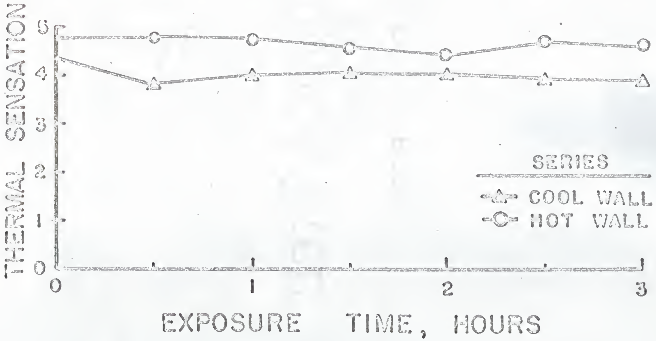

Figure 10. The Trend of Mean Thermal Sensation Votes with Exposure Time for the Subjects of the Cool and Hot Wall Series

The thermal sensations of females of the Hot Wall series were found to be independent of changes 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. (55) 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. (55) would be applicable. Some basis for this assumption can be obtained from the responses of thermal sensation of the subjects 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.

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, and noise level etc., may be of such magnitude that even the thermally "neutral" individual may experience discomfort. Where radiant panels are used, it is possible that the localized heating or cooling experienced by a person, due to the asymmetric MRT, may be sufficient to cause noticeable discomfort.

The comfort sensations of the subjects participating in the Cool Wall series were found to be not significantly different from the comfort sensations of subjects in the Control series. Therefore, although not all the thermally "neutral" subjects of the Cool Wall series felt comfortable, the cause of their discomfort could not be attributed to the asymmetric MRT.

The radiation shape factor by which each of the subjects were exposed to the cool wall was 0.20. This radiation factor was determined by assuming the subjects to be of spherical geometry, with centers two feet above floor level. The results of the analysis of variance, Appendix C, which indicates the response of thermal sensation were independent of seating position, support this assumption. The mean temperature of the cooled wall for the 10 tests was 60.3 F, its lowest temperature being 48 F.

The Cool Ceiling series was undertaken to determine if the presence of overhead cooling panels would cause discomfort to persons. 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 sensitive, exposed 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 MRT. 50 F is felt to be the lowest practical temperature the environmental engineer should encounter in typical situations because inside dew point temperatures lower than 50 F would be unusual. Of course direct contact with cooled panels would undoubtedly cause discomfort. Nevins (62) reports that both males and females found floor temperatures of 60 F objectionable to foot comfort.

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 (8). Chrenko correlated frequence 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 (8) 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 EMRT of the Hot Ceiling series was found to be 10 F. It is felt that the criteria proposed by Chrenko (8) 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 Figure (8) it is obvious that the probability of feeling "comfortable" varies considerably with a person's thermal sensation. Therefore, it seems imperative that the thermal sensations of subjects evaluating the relative comfort of various degrees of MRT asymmetry should be constant in order that the comfort comparison be of greatest meaning. 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 (9) 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 Hot Wall series show that the probability of a person feeling comfortable when exposed with a 0.20 radiation factor to a 130 F panel is significantly lower than for a person in a uniform environment. The modified comfort ballot, Figure (5), was employed to determine the causes of discomfort for the subjects of the Hot Wall series. The results, see Table (4), indicate that it was indeed the asymmetric MRT which caused the increase in discomfort relative to a uniform environment. The temperature of the heated wall was 130 F for all tests. The results of the regression analysis performed on the thermal sensations and the analysis of the comfort sensations of the votes of thermal comfort of subjects participating in the Hot Wall series, both indicate that thermal environments of this type should be avoided.

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 a insulation value of 0.6 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 facotrs 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 in 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. 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 mean radiant temperature.
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.

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APPENDICES

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.

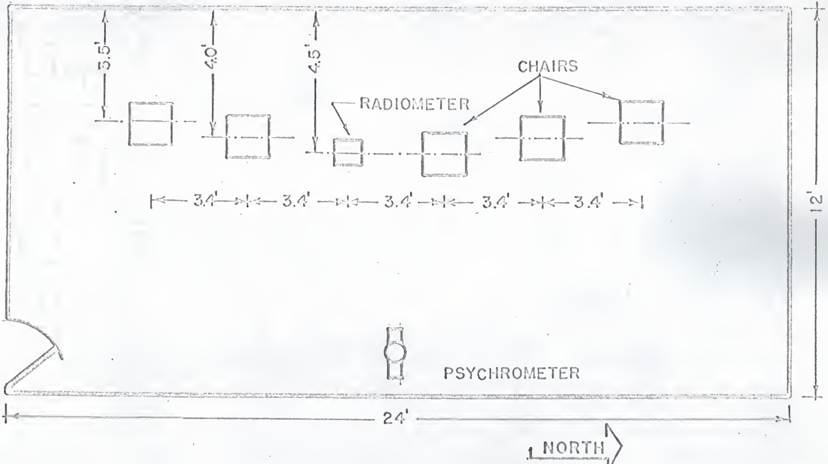

Figure A-1. The Position of the Subjects and Radiometer for the Cool and Hot Wall Series

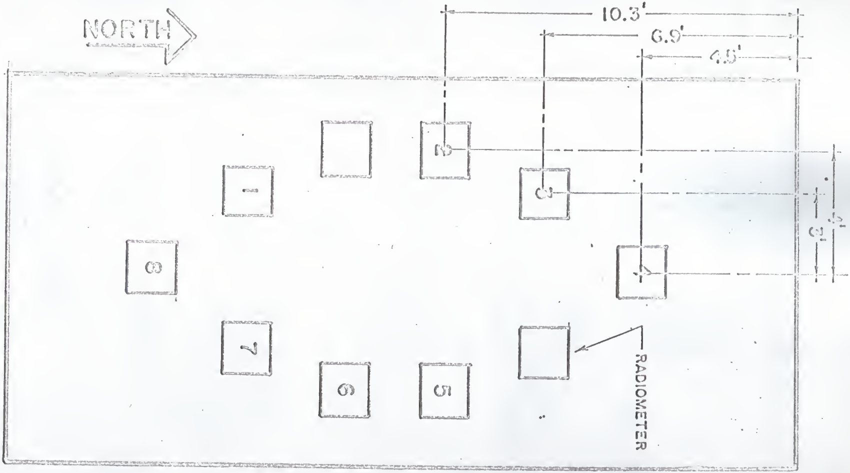

Figure A-2. The Position of the Subjects and Radiometer for the Cool and Hot Ceiling Series

APPENDIX B

INDOCTRINATION INFORMATION: Read to Subjects Before Each Test

The purpose of this test is to determine the effect of temperature on how you feel. As soon as preparations are completed in the pre-test room, we will take you into the room next door. Select the chair which is marked with the number you have been assigned and be seated. Do not move your chair from its original location. This is important so let me repeat: "Do not move your chair from its original location!"

During the test, you may read, study, or engage in quiet conversation. You may smoke but keep it to a minimum. At various intervals, you will be asked to vote on your feeling of thermal sensation and your feeling of comfort. You will record your votes on the two separate ballots provided. Do not discuss your votes with one another. Remember we want to know the way you feel at the time the ballot is handed to you!

Water will be provided and since the amount you drink will be measured you should drink only out of the cup assigned to you, but you may have all the water you wish.

When the test is completed return to the dressing room and get dressed. Place your uniforms and socks in one pile in the dressing room.

All person's 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

Tables C-1 and C-2 show the results of the analyses of variance to determine if the thermal sensations of the subjects of the Cool Wall and Hot Wall series were independent of their seating position. A 5% level of significance was assumed.

Table C-1

Analysis of Variance to Determine Independence of Thermal Sensation on Position for the Subjects Participating in the Cool Wall Series

Source of Variation	Degrees of Freedom	Corrected Sum of Squares	Mean Square	F
Conditions	9	97.1100	10.790	
Position	4	1.8205	0.455	.96 ns*
Sex	1	0.4462	0.446	
Interactions				
Cond:Pos	36	15.3136	0.425	.90 ns
Cond:Sex	9	15.9919	1.780	
Pos:Sex	4	1.2809	0.320	.67 ns
Error	36	17.1608	0.475	
Total	99	149.0699		

* ns = not significant

Table C-2

Analysis of Variance to Determine Independence of Thermal Sensation on Position for the Subjects Participating in the Hot Wall Series

Source of Variation	Degrees of Freedom	Corrected Sum of Squares	Mean Square	F
Conditions	6	55.1681	9.195	
Position	4	3.3762	0.844	1.60 ns
Sex	1	0.1955	0.196	
Interactions				
Cond:Pos	24	13.4011	0.558	1.06 ns
Cond:Sex	6	14.0653	2.344	
Pos:Sex	4	4.0209	1.005	1.90 ns
Error	24	12.6608	0.528	
Total	69	102.8879		

APPENDIX D

The linear radiation heat transfer coefficient was evaluated by:

$$h_r = \frac{e\,\sigma\left[(t_{cl} + 460)^4 - (t_{mrt} + 460)^4\right]}{(t_{cl} - t_{mrt})}$$

where:

h_r = linear radiation heat transfer coefficient, $BTU/hr\text{-}ft^2\text{-}F$

e = emissivity of the outer surface of the clothed body

σ = the Stephan-Boltzmann constant, $BTU/hr\text{-}ft^2\text{-}R^4$

t_{cl} = the average temperature of the outer surface of the clothed body, F

t_{mrt} = mean radiant temperature, F

Table E-1 shows the calculated values of h_r for values of t_{cl} of 85-88 F for the range of t_{mrt} investigated. The maximum error incurred by using a value of 1.04 for h_r is seen to be approximately 3%.

Table D-1

The Calculated Value of the Linear Radiation Coefficient for the Range of MRT Investigated

t_{cl} (F)	h_r* (BTU/hr-ft^2-F)				
	t_{mrt} (F)				
	70	75	80	85	90
85	1.01	1.02	1.04	-	1.07
86	1.01	1.03	1.04	1.05	1.07
87	1.01	1.03	1.04	1.05	1.07
88	1.02	1.03	1.04	1.06	1.07

* The emissivity of the outer surface of the clothed body taken as 0.95

$$\frac{1.04 - 1.01}{1.04} = \frac{1.07 - 1.04}{1.04} = 0.03 = 3\%$$

APPENDIX E

Prior to each testing session the subjects were questioned by the nurse for information which might explain any unusual response. On the following page is shown the data sheet used by the nurse for this pupose.

DBT: ____________ RH: ____________

MRT: ____________ WBT: ____________

Activity

WWT:

Bal T:

Ceiling T:

Name	Oral Temperature	Pulse	Time Subject Went to Bed (Military)	Hours of Sleep	Hours on Job During Past 21 Hours	Mental Exertion During past 21 Hours	Physical Exertion During past 21 Hours	Last Meal Time and Size	Alchol consumed During past 21 Hours	Health (Extent of Illness)	Health (Location of Illness)	Is Subject Menstruating?	Days Since End of Previous Menstruati		Degree of Concentration-Time of Vote	Degree of Concentration-Time of Vote	Degree of Concentration-Time of Vote	Degree of Concentration-Time of Vote	Degree of Concentration-Time of Vote	Degree of Concentration-Time of Vote	Degree of Concentration-Time of Vote	
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10.																						
11.																						
12.																						

Meal Size:

0	none
1	light
2	medium
3	heavy

Last Normal Meal Time

1	breakfast
2	lunch
3	dinner

Health (location):

0	well
1	head
2	nose
3	throat
4	stomach
5	1 & 3
6	2 & 3
7	1 & 2
8	all over
9	other

Health (Extent):

0	well
1	slightly sick
2	sick
3	very sick

Mental Exertion:

1	light
2	medium
3	heavy

Physical Exertion:

1	light
2	medium
3	heavy

Degree of Concentration

1	light
2	medium
3	heavy

Alcohol Drunk:

0	none
1	minimu socially acceptable
2	more

Menstruation

0	no
1	yes
3	male

VITA

Ronald E. Biddison

Master of Science

Thesis: THE EFFECT OF ENCLOSURE SURFACES, WITH TEMPERATURE SEPARATIONS RANGING TO 75F, ON THE THERMAL AND COMFORT SENSATIONS OF SEDENTARY SUBJECTS

Major Field: Mechanical Engineering

Biographical:

Personal Data: Born in Holton, Kansas, June 13, 1943, the son of Wilber G. and Lillie Biddison

Education: Attended grade school in Jackson County Kansas; graduated from Holton High School in 1961; received a Bachelor of Science degree in Mechanical Engineering from Kansas State University, Manhattan, Kansas, January, 1967; completed requirements for Master of Science degree in Mechanical Engineering in January, 1969.

Professional Experience: Employed by Chevrolet Metal Fabricating, Flint, Michigan as a student trainee in the automation section the summer of 1966; worked at the Institute for Environmental Research at Kansas State University from February, 1967, to January, 1969, conducting environmental studies on human comfort, a part of which are described in this thesis.

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THE EFFECT OF ENCLOSURE SURFACES, WITH TEMPERATURE SEPARATIONS RANGING TO 75F, ON THE THERMAL AND COMFORT SENSATIONS OF SEDENTARY SUBJECTS

by

RONALD EUGENE BIDDISON

B. S., Kansas State University, 1967

AN ABSTRACT OF A THESIS

submitted in partial fulfillment of the

requirements for the degree

MASTER OF SCIENCE

Department of Mechanical Engineering

KANSAS STATE UNIVERSITY
Manhattan, Kansas

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ABSTRACT

A study was conducted to determine the effect of asymmetric mean radiant temperature (MRT) on the thermal and comfort sensations of sedentary subjects. Four separate series of tests were performed in order to investigate the conditions of asymmetric MRT most frequently encountered in the field. An experimental design was selected such that direct comparison of the responses of thermal sensations of the subjects of the present study could be made with the corresponding responses of subjects exposed to uniform enclosure temperatures from a previous study. The effect of asymmetric MRT on subjects' comfort sensations was examined by comparison of the comfort response of subjects exposed to an asymmetric MRT with the comfort response of subjects exposed to uniform enclosure temperatures equal to air temperature.

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 0.6 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. 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 mean radiant temperature.
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.