NBSIR 82-2585 (DOE)

Thermal Comfort in Passive Solar Buildings -- An Annotated Bibliography

U.S. DEPARTMENT OF COMMERCE
National Bureau of Standards
National Engineering Laboratory
Center for Building Technology
Washington, DC 20234

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THERMAL COMFORT IN PASSIVE SOLAR BUILDINGS -- AN ANNOTATED BIBLIOGRAPHY

Arthur Rubin

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U.S. DEPARTMENT OF COMMERCE, Malcolm Baldrige, *Secretary*
NATIONAL BUREAU OF STANDARDS, Ernest Ambler, *Director*

ABSTRACT

This study consists of a selective annotated bibliography of thermal comfort research organized around major subject areas, and recommendations for future research concerned with thermal comfort in passive solar buildings. No attempt has been made to provide a comprehensive treatment of this extensive area of investigation — as this would be beyond the scope of the project under which this work was performed. Instead, the intent has been to sample the range of experimental variables and research methods employed by thermal comfort researchers -- and to indicate significant findings.

The major goals for the present report are to describe the state-of-the-art of thermal comfort research and findings and to indicate the research needed to develop the information required by those responsible for specifying, designing and operating passive solar buildings.

FOREWORD

This report covers work by the National Bureau of Standards under Contract DE-AI01-76PR06010 with the U.S. Department of Energy. The work was sponsored by the Passive and Hybrid Solar Energy Division, Office of Solar Heat Technologies, U.S. Department of Energy, Washington, D.C. 20545, under Interagency Agreement No. EA-77A-01-6010.

The author of the report would like to express his appreciation to Dr. Larry Berglund of the John Pierce Foundation for reviewing the report prior to publication. Other major contributions were made by Mrs. Mary Ramsburg, who typed the document, and Mr. Keith Mackley, who prepared the illustrations.

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1. INTRODUCTION

The subject area of thermal comfort in passive solar buildings has received very little attention by researchers, and until quite recently, has scarcely been considered at all by them. Consequently, a review of work dealing only with this problem area would cover only a "handful" of preliminary studies -- and these are typically in the nature of case studies by architects without any research training. The present report therefore describes a range of studies which typify thermal comfort research procedures and findings, and therefore must be considered by those engaged in passive solar thermal comfort work. Special emphasis is placed upon recent investigations of thermal asymmetry -- a subject of particular importance in passive solar buildings. The response to temperature drifts has also been noted for reasons of energy conservation as well as its relevance to passive solar designs.

This study consists of a selective annotated bibliography of thermal comfort research organized around major subject areas, and recommendations for future research concerned with thermal comfort in passive solar buildings. No attempt has been made to provide a comprehensive treatment of this extensive area of investigation -- as this would be beyond the scope of the project under which this work was performed. Instead, the intent has been to sample the range of experimental variables and research methods employed by thermal comfort researchers -- and to indicate significant findings.

While considerable efforts have been devoted to the development of computer models of passive solar designs, this topic is only touched upon in the present report -- which focuses on the behavioral and physiological factors which influence thermal comfort. For the most part the computer modeling studies have used various thermal comfort models to assess the effects of proposed engineering and architectural solutions, and have not dealt substantively with thermal comfort issues.

The major goals for the present report are to describe the state-of-the-art of thermal comfort research and findings and to indicate the research needed to develop the information required by those responsible for specifying, designing and operating passive solar buildings.

2. THERMAL COMFORT

Whether an occupant finds an environment thermally acceptable or not is primarily due to the energy transfer between the person and the environment and the physiological difficulty in regulating this flow so that metabolic energy production balances the losses to the surroundings. Environmental and personal parameters effect this change. The environmental ones are temperature,* radiation, humidity, and air movement. The important personal parameters are clothing and activity. In addition thermal nonuniformities in the space such as localized drafts, temperature variation, and radiant asymmetry can cause local discomfort that detracts from the overall perceptions of the occupant. The following section of the bibliography reviews articles on thermal comfort that are applicable to passive solar design.

2.1 DESCRIPTION OF THERMAL COMFORT

A scientific understanding of thermal comfort can be traced to early studies (in the 1920's). Since that time, researchers have identified several basic variables as noted above, while more recent investigations have focused on obtaining improved quantitative data, and summarizing findings for design applications.

Houghton and Yagloglou pioneered research efforts to define the thermal comfort zone of acceptability for temperature and humidity conditions, and the development of "equal comfort lines". McNall and Schlegel examined the relative effects of convective and radiation heat transfer on thermal comfort. The work of Nevins, et al., and Rohles served to update the early work with respect to the quantity and the quality of the data available, and the summarization of their findings in chart form. Olesen and Fanger described the skin temperature distribution for subjects in thermally neutral conditions. McNall, Ryan, and Jaax examined the effects of seasonal variation in comfort conditions. (The reference books described in section 8 of the present work provide extensive treatments of these factors.)

- Houghton, F. C. and Yagloglou, C. P. "Determination of the comfort zone." ASHVE Transactions, 29, (1923).

This study is of one of earliest (and most cited) investigation of thermal comfort. Its goal was to define a comfort zone and a line of maximum comfort within this zone. The boundaries of the zone were investigated, using 30 and 60 percent relative humidities and defining the upper and lower temperature limits by approaching them from both higher and lower temperatures to compensate for any acclimatization effects. Another aim for the study was to verify the slope of the effective temperature lines in the comfort region by questioning subjects about their reactions as follows: Is this condition comfortable or uncomfortable?; Do you desire a change?; If so, do you prefer warmer

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* For the purposes of this report, "air temperature" means "dry bulb temperature" unless noted otherwise.

or cooler? Subjects spent one and one half hours in one room with a given temperature and a like amount of time in another room with a different temperature, recording their votes at 15 minute intervals.

Subjects wore different types of clothing and were seated and engaged in light activities such as card playing, reading and writing. Twelve subjects were exposed to the test conditions for 3 hours; 14 subjects for 2 hours and 100 subjects for about 15 minutes. The comfort zone was defined as including effective temperatures over which 50 percent of the people are comfortable. On this basis, the zone limits were found to be 62 and 69°F ET (16.7 and 20.6°C), with a comfort line of 64°F (17.8°C) ET.

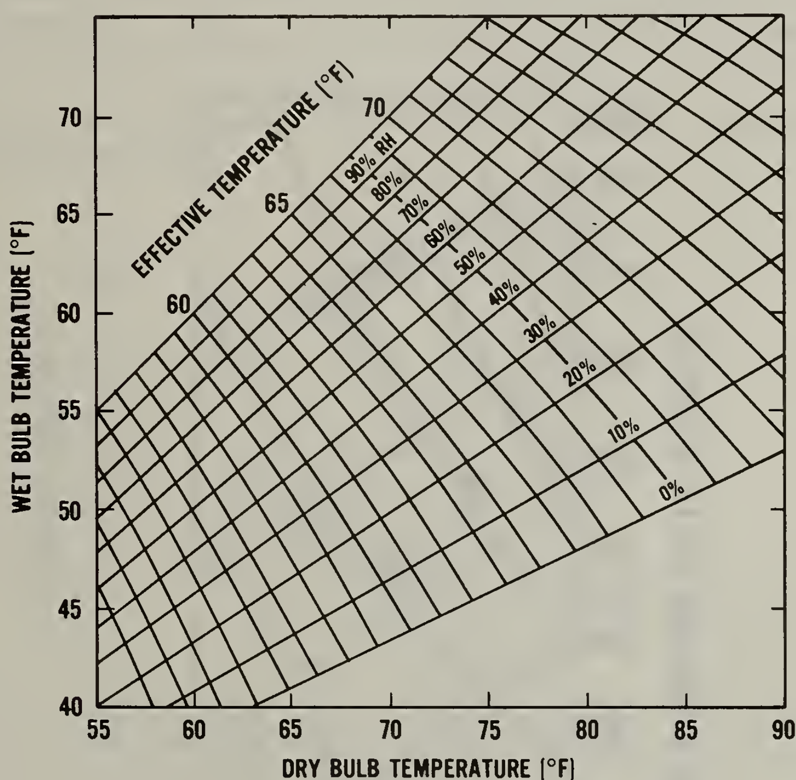

Figure 1. Proposed chart to the used in connection with the synthetic air chart.

- Houghton, F. C. and Yagloglou, C. P. "Determining lines of equal comfort." ASHVE Transactions, 29, (1923).

This study is another of the "classic" investigations of thermal comfort. The authors hypothesized that there must be certain combinations of temperatures and humidities which produce the same total body heat loss by radiation and convection and therefore the same feeling of comfort or discomfort. Lines passing through such air conditions may be called "equal comfort lines". The present investigation was to determine equal comfort lines for still air conditions.

In the experiment, observers moved from one room to another one, recording their judgments about the relative feeling of warmth of the two conditions. The fixed condition in one room was a relatively high dry bulb temperature and low relative humidity. The atmosphere in the comparison room was then changed by lowering the temperature and raising the relative humidity until it was judged to be cooler than the test room. The dry (or wet) bulb temperature was then raised while observers went back and forth between the rooms until the rooms were judged to be equal in warmth. This procedure was followed 440 times--and the data obtained was used to formulate the equal comfort curve chart (below). (Details regarding subjects, clothing, activity, etc. were not reported.)

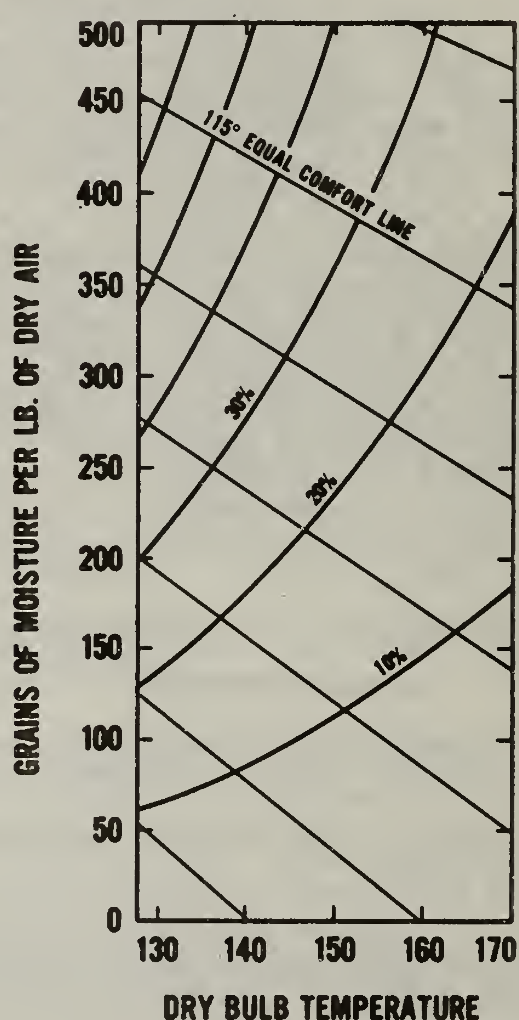

Figure 2. Equal comfort curves. (Houghton and Yagloglou)

• McNall, P. E. and Schlegel, J. C. "The relative effects of convection and radiant heat transfer on thermal comfort (thermal neutrality) for sedentary and active human subjects." ASHRAE Transactions, 74, Part 2, (1968).

This study investigated the relative importance of mean radiant temperature (MRT) and air temperature in and near the zone of thermal neutrality for people engaging in sedentary and active tasks. A series of eight combinations of MRT and air temperatures in the range of 70 to 90°F (20.1 to 32.23°C), with a fixed RH or 45 percent, were the experimental conditions. The mean air velocity was between 25 and 30 fpm. The sedentary activity consisted of reading and engaging in conversations. The "work" activity consisted of subjects taking one step per second over a block of two--9 inch steps for 5 minutes, followed by a rest period of 10 minutes. This cycle was continued for the duration of the 3 hour test session. At half hour intervals subjects recorded their thermal sensations on a 7 point scale.

The results showed generally good agreement with Fanger's comfort equation for the conditions studied (15).

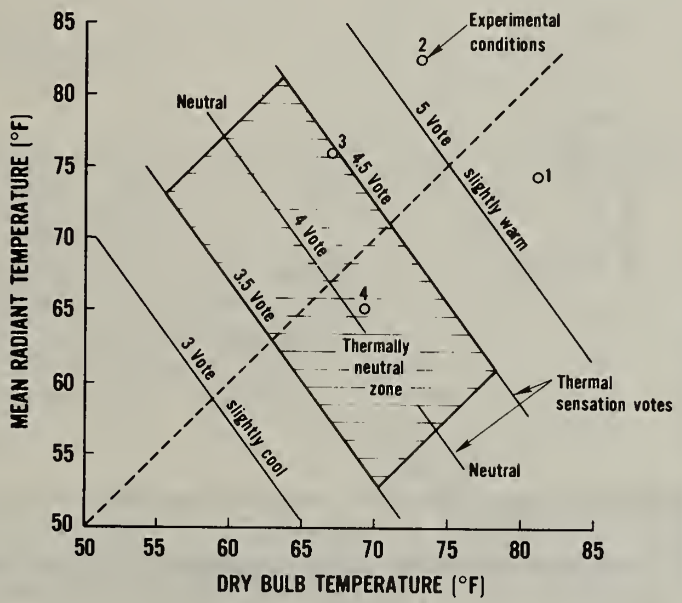

Figure 3. MRT vs air temperature showing the predicted 3.0, 4.0, and 5.0 thermal sensation vote lines for active males and females combined (metabolic rates were approximately 830 Btuh for the females). The experimental conditions are noted and the suggested zone of thermal neutrality is shown. (McNall and Schlegel).

• Nevins, R. G., Rohles, F. H., Springer, W., and Feyerherm, A. M. "Temperature-humidity chart for thermal comfort of seated persons". ASHRAE Transactions, 72, Part 1, (1966).

This study was an examination of the relationship of temperature and humidity on thermal comfort. Seven hundred and twenty college students (360 males, 360 females) participated in the experiment in groups of 10, wearing a standard uniform of 0.52 clo. The temperatures examined ranged from 66 to 82°F (18.9 to 27.1°C) (at intervals of 2°F (1.1°C), while relative humidity (RH) was varied from 15 to 85 percent (at 10 percent intervals). Air velocities were less than 45 fpm in all instances. The experimental sessions were of 3 hours duration, half conducted in the afternoon and the remainder in the evenings.

Subjects reported to a pre-test room for 30 minutes, at which time they were given instructions about the study and how to complete the 7 point thermal comfort ballot. They were then taken to the test room, and after 1 hour were told to record their thermal comfort votes; they voted at half hour intervals afterward, until the end of the study. Skin temperature, rectal temperature, and heart rate data were also collected. During the study, the subjects remained seated and most of them read, studied or played cards. The major findings of the study are summarized in the figure below.

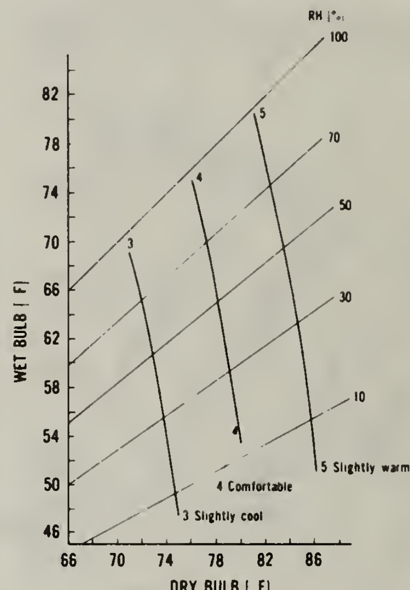

Figure 4. Revised comfort chart derived from this study. (Nevins, et al.).

- Rohles, F. H., Jr. "Thermal sensations of sedentary man in moderate temperatures." Kansas State Univ., Manhattan, Kansas, Special Report, June 1970.

This study examined the range of thermal conditions at which sedentary subjects reported that they were comfortable. One thousand six hundred college age students were exposed in groups of 10 subjects each (five men, five women) to 20 different dry bulb temperatures ranging from 60°F to 98°F (15.6 to 36.7°C), in 2°F (1.1°C) increments at each of eight relative humidities: 15, 25, 35, 45, 55, 65, 75, and 85 percent for 3 hours. Thermal sensations were recorded every half hour.

The results showed that in clothing of 0.6 clo, the range of "comfortable" votes was from 62°F to 98°F (16.7 to 36.7°C). Other findings are summarized in figures 5 and 6, below.

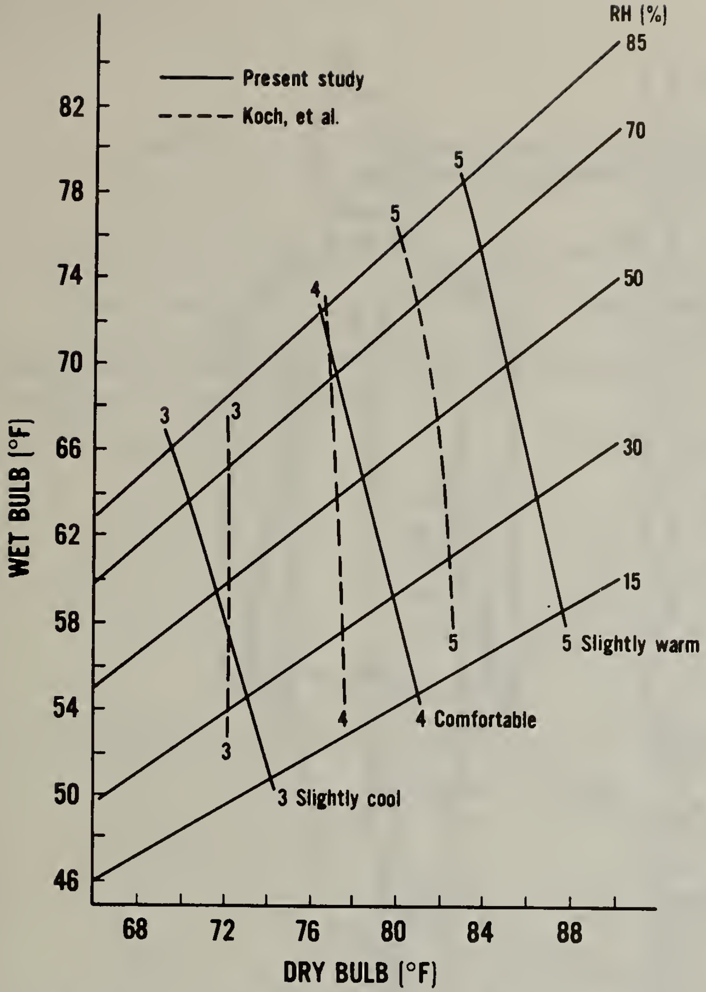

Figure 5. A comparison of the ASHRAE Standard for Thermal Comfort 55-66 (cross-hatched area) and the results of the present study. (Rohles)

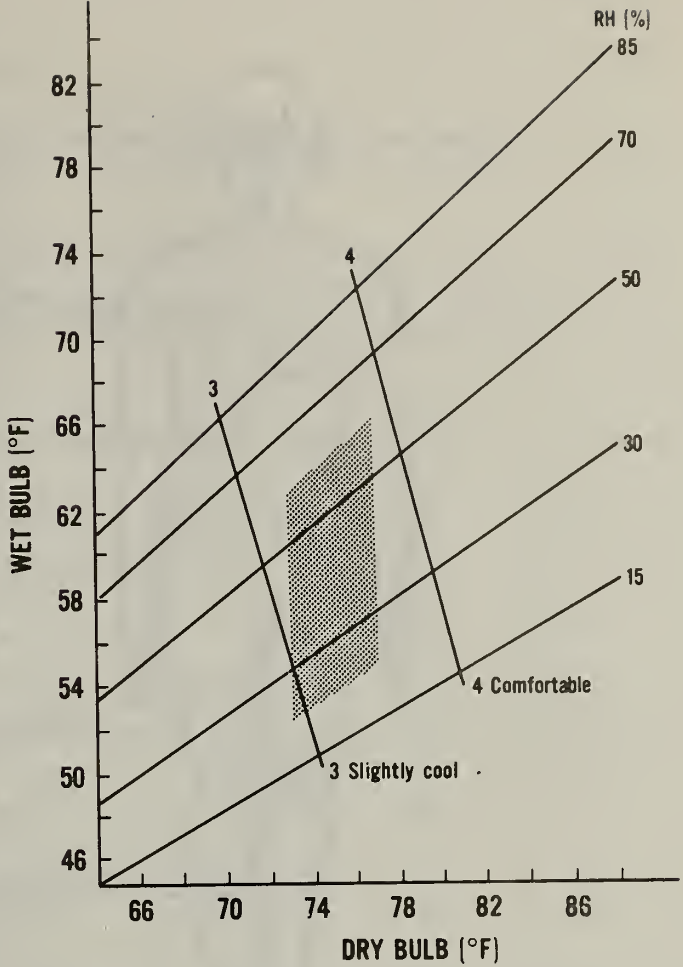

Figure 6. A comparison of the lines of thermal sensation for the present study and those of Koch, et al. (Rohles)

- Olesen, B. W. and Fanger, P. O. "The skin temperature distribution for resting man in comfort." Symposium on Quantitative Prediction of the Physiological and Psychological Effects of the Thermal Environment in Man. Stasbourg, France, July 9-13, 1973.

This study examined skin temperatures of subjects who were in thermally neutral condition. Thirty-two subjects (16 male, 16 female) participated in the investigation, which required them to be sedentary and wear standard cotton uniforms (0.6 clo). Skin temperatures were measured at 14 locations on the skin surface (see figure 7). During the study, the subjects read, studied, or performed equally quiet activities. At 5 minute intervals, all temperatures were measured and recorded on a data logging system.

On the average, males and females preferred the same ambient temperature (25.5°C) and had the same mean skin temperature (33.5°C). Female subjects displayed less uniform skin temperatures than males -- standard deviations for the females being 1.43°C, and 1.04°C, for the men.

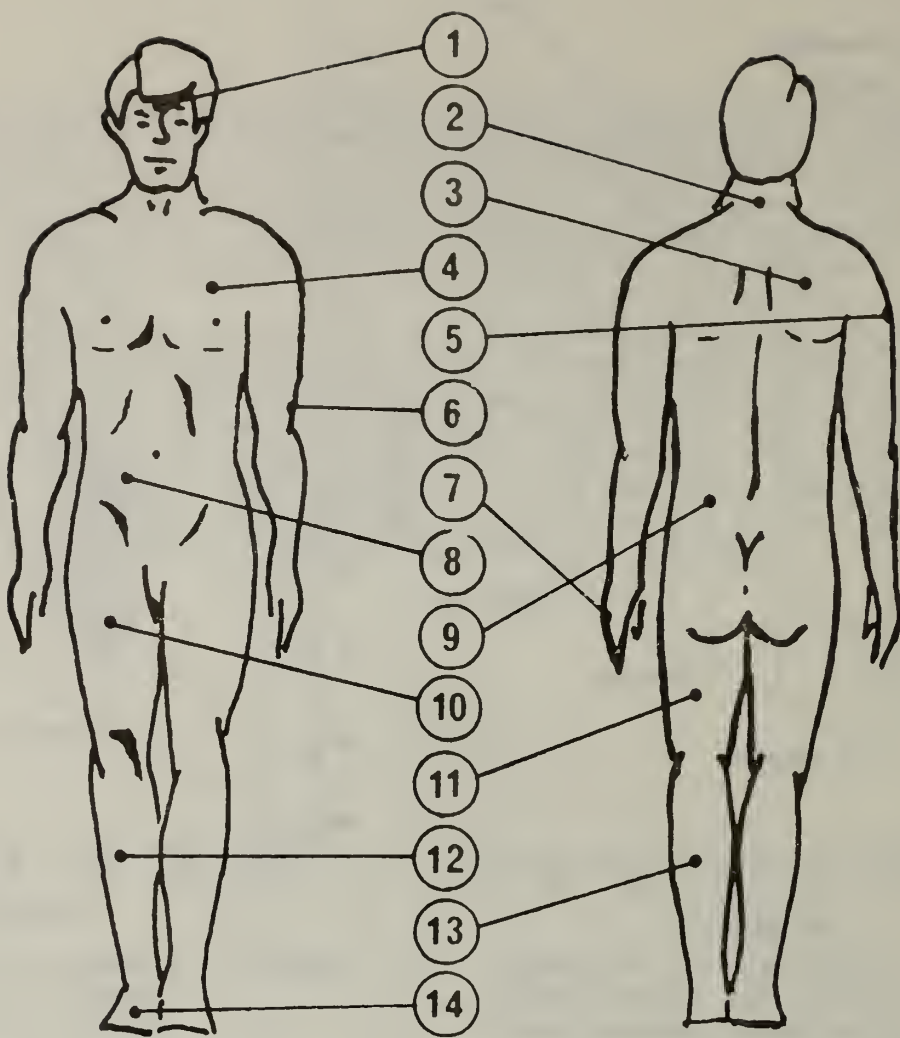

Figure 7. Location of skin temperature sensors. (Olesen and Fanger)

- McNall, P. E., Ryan, P. W. and Jaax, J. "Seasonal variation in comfort conditions for college-age persons in the middle west. ASHRAE Transactions 74, Part 1, (1968).

This study was a partial replication of an earlier investigation performed during the winter season. The intent was to determine whether thermal comfort data is influenced by seasonal variations. The investigation was conducted during the summer of 1966 in Manhattan, Kansas. Ninety subjects participated; half were males and half were females. The study lasted three hours, and like the earlier experiment, subjects wore standard uniforms, were seated and permitted to read, study, play cards, or quietly converse. Three humidities were used--25 percent, 55 percent, and 85 percent. Air velocities in the chamber were between 20 and 30 fpm. Subjects responded on a seven point scale.

In general, no significant differences were found with respect to thermal comfort when winter season data was compared with the findings of the summer study.

Table 1. Mean Thermal Sensation Votes, Males and Females Combined, for all Tests* (McNall, Ryan, and Jaax)

Test Condition		Season	Mean thermal sensation vote at the indicated time after entering the test condition				
Relative Humidity (°C)	Dry bulb temperature (F)**		1 hr	1 1/2 hr	2 hr	2 1/2 hr	3 hr
	74	summer	2.7	2.8	2.9	2.8	2.8
		winter	3.3	3.6	3.3	2.9	2.9
25	78	summer	4.0	3.9	4.0	3.6	3.6
		winter	4.1	4.1	4.0	4.1	3.9
	82	summer	4.6	4.5	4.5	4.9	4.7
		winter	4.6	4.2	4.9	4.3	4.4
	74	summer	3.6	3.8	3.7	3.5	3.5
		winter	3.5	3.4	3.0	2.9	3.3
55	78	summer	4.3	4.2	4.0	3.9	4.4
		winter	3.9	4.0	3.8	4.1	3.9
	82	summer	5.0	4.8	4.4	4.3	4.4
		winter	5.2	4.7	4.3	5.0	4.6
	74	summer	4.2	4.5	4.0	4.1	4.0
		winter	3.6	2.9	4.1	3.4	3.8
	78	summer	4.5	4.5	4.1	4.2	4.3
		winter	5.1	4.4	4.0	4.6	4.3
	82	summer	5.6	5.0	4.1	4.1	4.0
		winter	6.1	5.3	5.0	4.8	5.0

* These data comprise the mean votes for individual tests with only five subjects of each sex. Any single test is subject to individual variation and population sampling variation. Therefore, conclusions should not be drawn from limited comparisons among these data. Analyses employing all the data of this paper and also that of Nevins et al., are necessary to maximize the validity of the conclusions.

** Mean radiant temperature kept equal to dry bulb air temperature.

2.2 TEMPERATURE DRIFTS

One means of conserving energy in buildings has been by varying traditional operating procedures -- intended to provide uniform conditions. A method frequently employed is to minimize the use of HVAC systems in buildings containing considerable mass, and permit the temperatures to "drift" within specified limits. The utilization of building mass as an important design feature to regulate temperatures, is frequently encountered in passive solar buildings. As in studies of thermal asymmetry, research has focused on the influence of such temperature fluctuations on thermal comfort.

Wyon, et al., examined ambient temperature swings on comfort, performance, and behavior. Berglund and Gonzales examined occupant acceptability of 8 hour temperature ramps on feelings of thermal acceptability. The same authors investigated the effect of clothing differences on the acceptability of temperature drifts. Rohles, Milliken, and Krstic examined cyclical temperature fluctuations on judgments of thermal sensation and thermal comfort.

- Wyon, D. P., Ásgeirsdóttir, T., Kjerulf-Jensen, P., and Fanger, P. O. "The effects of ambient temperature swings on comfort, performance, and behavior." International Symposium on Quantitative Prediction of the Physiological and Psychological Effects of the Thermal Environment in Man, Strasbourg, France, July 9-13, 1973.

This paper is concerned with the effects of temperature changes on the behavioral, physiological, comfort, and performance responses of subjects. Sixteen subjects participated in the study (8 males, 8 females), two at a time, wearing standard cotton uniforms (0.6 clo). The study took place in a small climate chamber where participants engaged in mental tasks for the duration of the 7 1/2 hour study. Subjects were paired on the basis of having similar preferred ambient temperatures, and sinusoidal temperature swings took place about the average temperature. The following combinations of peak-to-peak amplitude and period were investigated: 0, 2, and 4°C, with a period of 8 minutes; 2, 6, and 8°C, with a period of 16 minutes; 4 and 8°C, with a period of 32 minutes.

These conditions were presented consecutively in a random order. Subjects assessed their degree of thermal comfort throughout the study using a dial voting device and marked semantic differential scales to record their "level of arousal", "degree of fatigue", and the "freshness of the air" under each condition. Skin temperatures were also recorded.

Significant differences were found with respect to skin temperatures, performance, and thermal comfort when the swing conditions were compared with constant conditions. Small, rapid swings of temperature were associated with decreases in the rate of working and the accuracy scores. Larger, slower swings of temperature were associated with somewhat faster rates of working, but were accompanied by feelings of being "too hot" and "too cold" at the extreme temperatures.

- Berglund, L. C. and Gonzalez, R. R. "Occupant acceptability of eight hour long temperature ramps in the summer at low and high humidities." ASHRAE Transactions, 84, Part 2, (1978).

This investigation is a followup to an earlier one which was designed to determine the effects of slow temperature changes on sensations of thermal comfort. The earlier investigation was of 4 hours duration; the present one examined 8 hour conditions.

The experiment consisted of testing subjects wearing summer clothing, exposed to three different environmental conditions. One condition served as a control and the temperature was kept constant at 21°C, with a dew point of 10°C. In the two experimental conditions, the temperature was raised at a rate of 0.6°C/h from 23°C to 27.8°C. In one condition the dew point was 10°C, and in the other one it was kept at 20°C. (10°C is the middle of the acceptable range of ASHRAE Standard 55-74; 20°C is the maximum dew point expected in a building during the summer.) The study took place in an environmental chamber, with six subjects tested simultaneously. At half hour intervals, subjects evaluated their environments in terms of thermal sensation, discomfort and thermal acceptability. Subjects engaged in sedentary tasks throughout the study.

The findings indicated that a temperature ramp of 0.6°C/h between 23°C and 27°C was acceptable to more than 80 percent of the subjects.

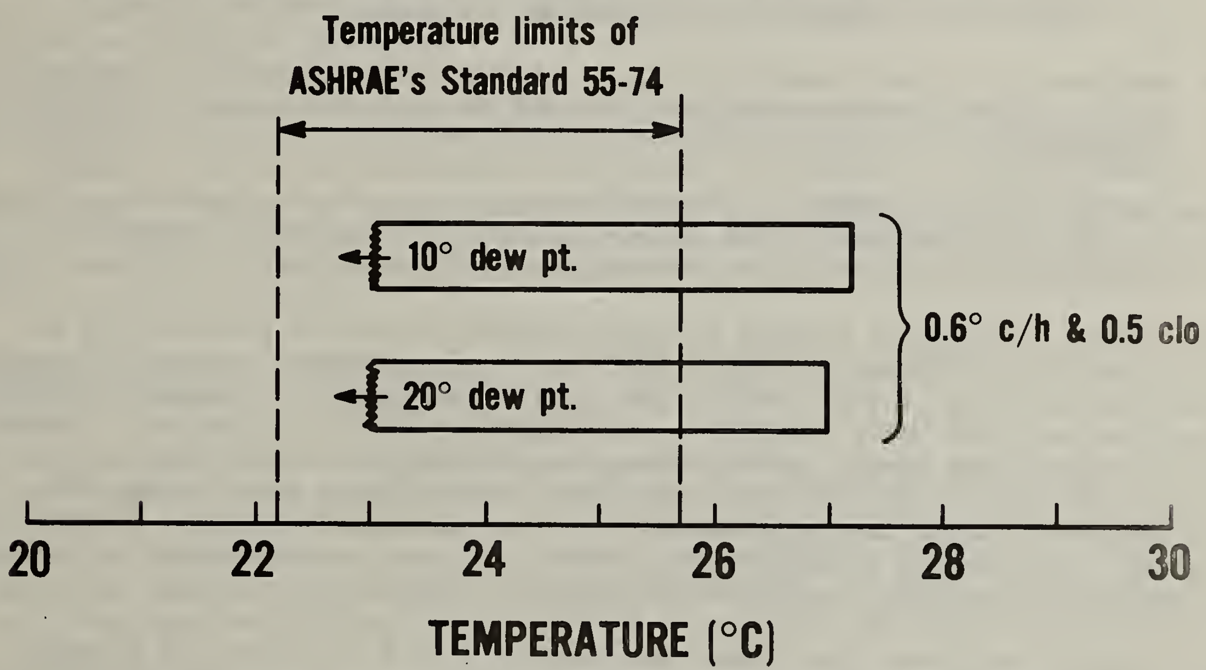

Figure 8. Comparison of present study's 80 percent thermal acceptability temperature limits with those of ASHRAE Standard 55-74. Note: (←) indicates 80 percent thermal acceptability temperature limit was not defined but lies beyond this point in direction of arrow. (Berglund and Gonzales)

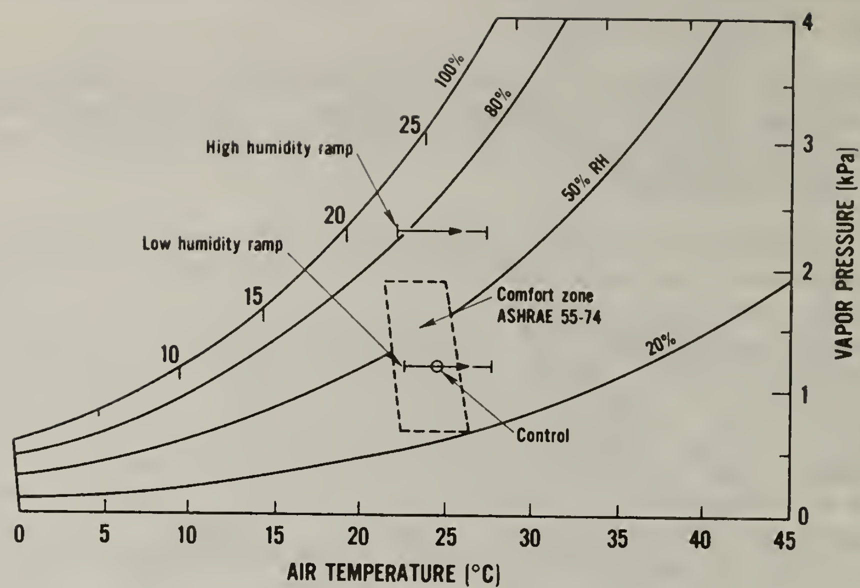

Figure 9. Summary of test findings. (Berglund and Gonzales)

- Berglund, L. G. and Gonzalez, R. R. "Application of acceptable temperature drifts to built environments as a mode of energy conservation." ASHRAE Transactions, 84, Part 1, No. 2476 (1978).

The present study examined the effects of temperature drifts upward and downward on the thermal acceptability of an environment. Another major variable investigated was the effects of clothing on such judgments.

The study consisted of testing subjects dressed in each of three levels of clothing (0.5, 0.7, and 0.9 clo). Each subject experienced a range of temperature changes from -1.5 C/h to +1. C/h, at .5C increments. A control condition was also employed, with a constant temperature of 25°C. Air and wall temperatures were always equal. Air movement and dewpoint point were kept constant at 0.1 m/s and 12°C, respectively. The study took place on seven consecutive afternoon sessions, lasting 4 hours each. The subjects engaged in sedentary tasks, e.g., reading or talking for most of the time, and responded to thermal conditions by marking 7 point scale ballots at half hour intervals.

The results indicated that temperature drifts of 0.5 C/h about the thermal neutral temperature are equivalent to preferred constant temperature conditions. (Neutral temperature being determined by the clothing level used.) Changes in rates of more than 0.5 C/h resulted in less acceptable comfort ratings.

- Rohles, F. H. Jr., Milliken, G. A. and Krstic, I. "The effect of cycled temperature fluctuations on thermal comfort." Kansas State Univ. (IER Report No. 79-01). Manhattan, Kansas, April 1979.

This experiment examined the effect of cyclical temperature fluctuations on thermal sensation and thermal comfort. Subjects were tested six at a time in a chamber where they engaged in activities such as working on anagrams and solving simple addition problems. Subjects filled out thermal comfort and thermal sensation ballots at regular interals and also had their skin temperatures monitored. The experimental conditions were 64, 67, 73, 79, and 85° FET* (17.8, 19.4, 22.8, 26.1, and 29.4°C), which fluctuated at the rates of 2, 4, 6, and 8°F (1.1, 2.2, 3.3, and 4.4°C) per hour.

The major conclusion of the study was that a thermal sensation cannot be associated with a given thermal condition unless we define "how", in terms of time, the subjects arrived at that temperature. For example, a fast temperature rise to a particular level results in a different sensation from one resulting from a slow rise in temperature.

2.3 THERMAL ASYMMETRY

Many passive solar building designs produce conditions of thermal asymmetry because of the design features used to collect and/or store heat. Since traditional designs of HVAC sytems are based on the assumption that uniform thermal conditions are optimal for thermal comfort, it is necessary to determine the effects of thermal asymmetries on feelings of thermal comfort. Fortunately, even before the advent of solar designs, researchers have been interested in non-uniformities of building thermal conditions. A variety of such asymmetries have been studied experimentally.

Houghton and McDermott, Schlegel and McNall, and Olesen, et al., all systematically varied wall temperatures to examine the effect on thermal comfort. Michaels, Nevins and Feyerherm, and Nevins and Feyerherm examined floor surface temperatures with respect to thermal comfort. Fanger, et al., examined the comfort limits for heated ceilings. Finally, McNall and Biddison, and McIntyre examined ceiling and wall temperatures to determine their effects on feelings on thermal comfort.

- Houghton, F. C. and McDermott, P. "Cold walls and their relation to the feeling of warmth." ASHVE Transactions, 39, (1933).

This study was performed by placing the subjects inside a small room where the temperature of the three walls and the air temperature could be controlled separately. An adjacent room was provided where the room surfaces and the air temperatures were the same as the test room. The subjects moved between the two rooms and recorded their subjective thermal sensations. The three sides of the test room were varied from 45° to 60°F (7.2 to 15.6°C) dry bulb temperature.

The effect of the subject's proximity to the cold walls appeared to be almost entirely dependent upon the change of the solid angle of exposure. As the temperature of the three side walls was decreased, a corresponding increase in air temperature was required to maintain the thermal sensation as equivalent to various environments where the air temperature and the mean radiant temperature were identical. The effect can be shown as in figure 10, where the wall temperature is shown as the abscissa, the required increase in air temperature is represented by the ordinate, and the lines of constant sensation are shown for an equivalent situation, where the mean radiant temperature equals the air temperature.

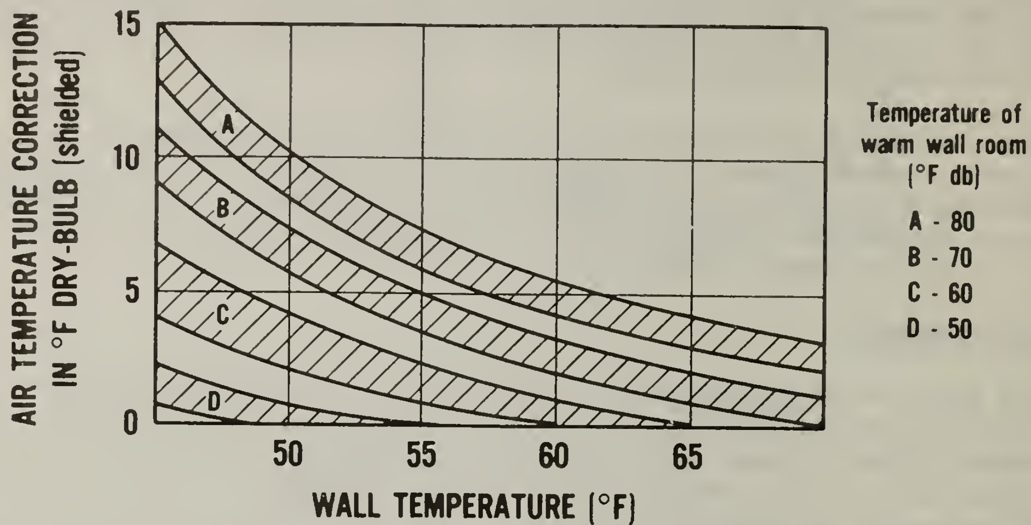

Figure 10. Cold wall study findings on feelings of warmth. (Houghton and McDermott)

- Schlegel, J. C. and McNall, P. E. "The effect of asymmetric radiation on the thermal and comfort sensations of sedentary subjects", ASHRAE Transactions, 74, Part 2, (1968).

This study was conducted to determine if a person may feel uncomfortable due to non-uniformity of the mean radiant temperature (MRT), and to examine the acceptable limits of asymmetry. The comfort sensation ballot consisted of the following choices: A. Uncomfortable, B. Slightly Uncomfortable, C. Uncomfortable, D. Very Uncomfortable, E. Intolerable. Sixty subjects (40 male, 20 female) were exposed to a combination of asymmetric MRT's, that were predicted to evoke thermal sensation votes between 3 and 5 on a scale ranging from 1-7, with 1 = "COLD" and 7 = "HOT". The subjects wore standard KSU uniforms (0.59 clo). During the three hour duration of the experiment, thermal sensation ballots were filled out every half hour. Votes on comfort sensation were taken 5 minutes after the thermal sensation ballots were collected.

In the study, the wall temperature of the experimental wall was lowered (or raised) 10°F (5.5°F) relative to the air temperature, and the temperatures of the other surfaces were raised (or lowered) 2.5°F (1.4°C) relative to the air temperature. By these means, the MRT was expected to be equal to the air temperature at the position of the subject.

The authors found no significant discomfort attributable to asymmetry under the conditions examined. The thermally neutral zone developed in earlier studies under symmetrical MRT, held for the asymmetric conditions studied in the present experiment.

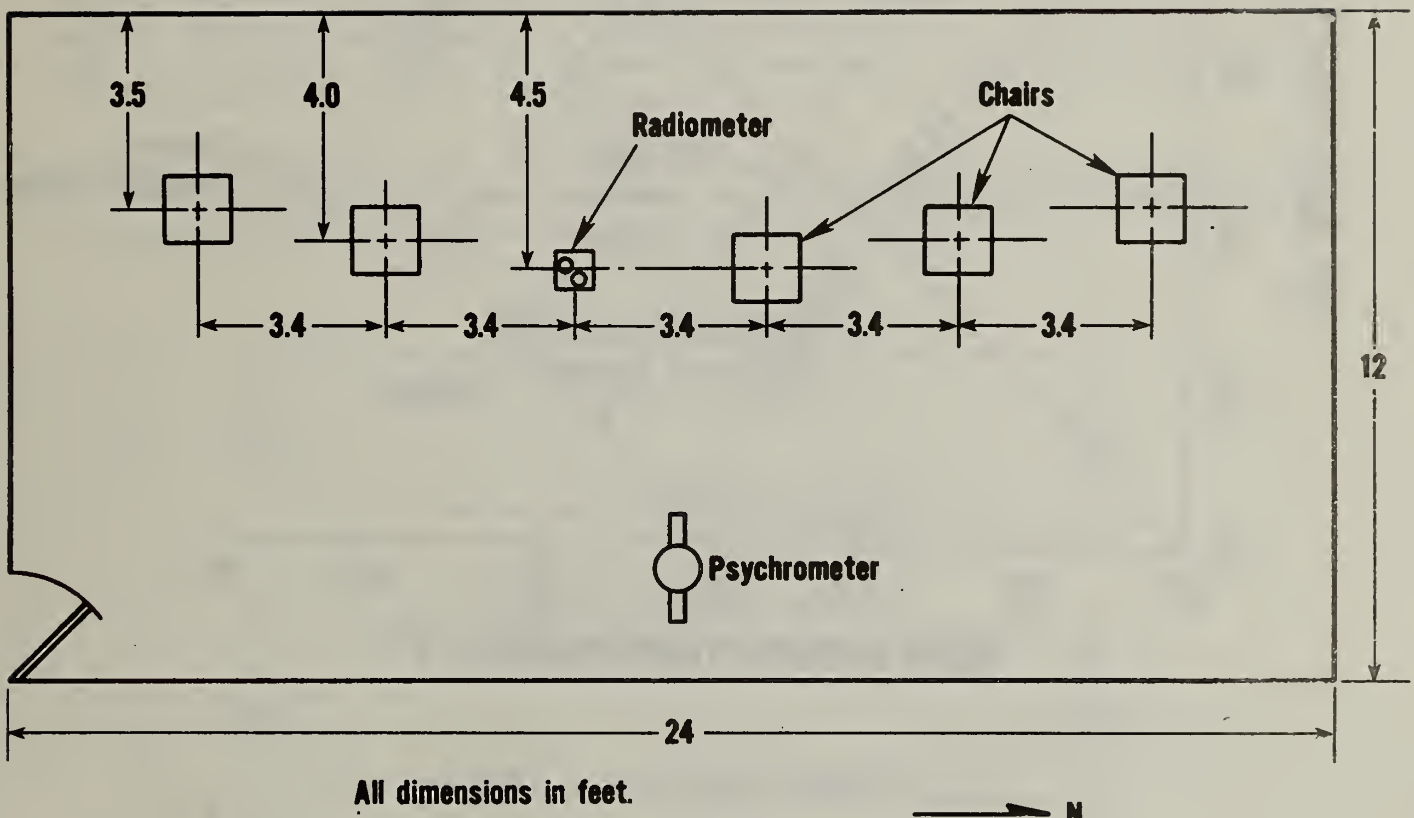

Figure 11. A plan view of the experimental test chamber. (Schlegel and McNall)

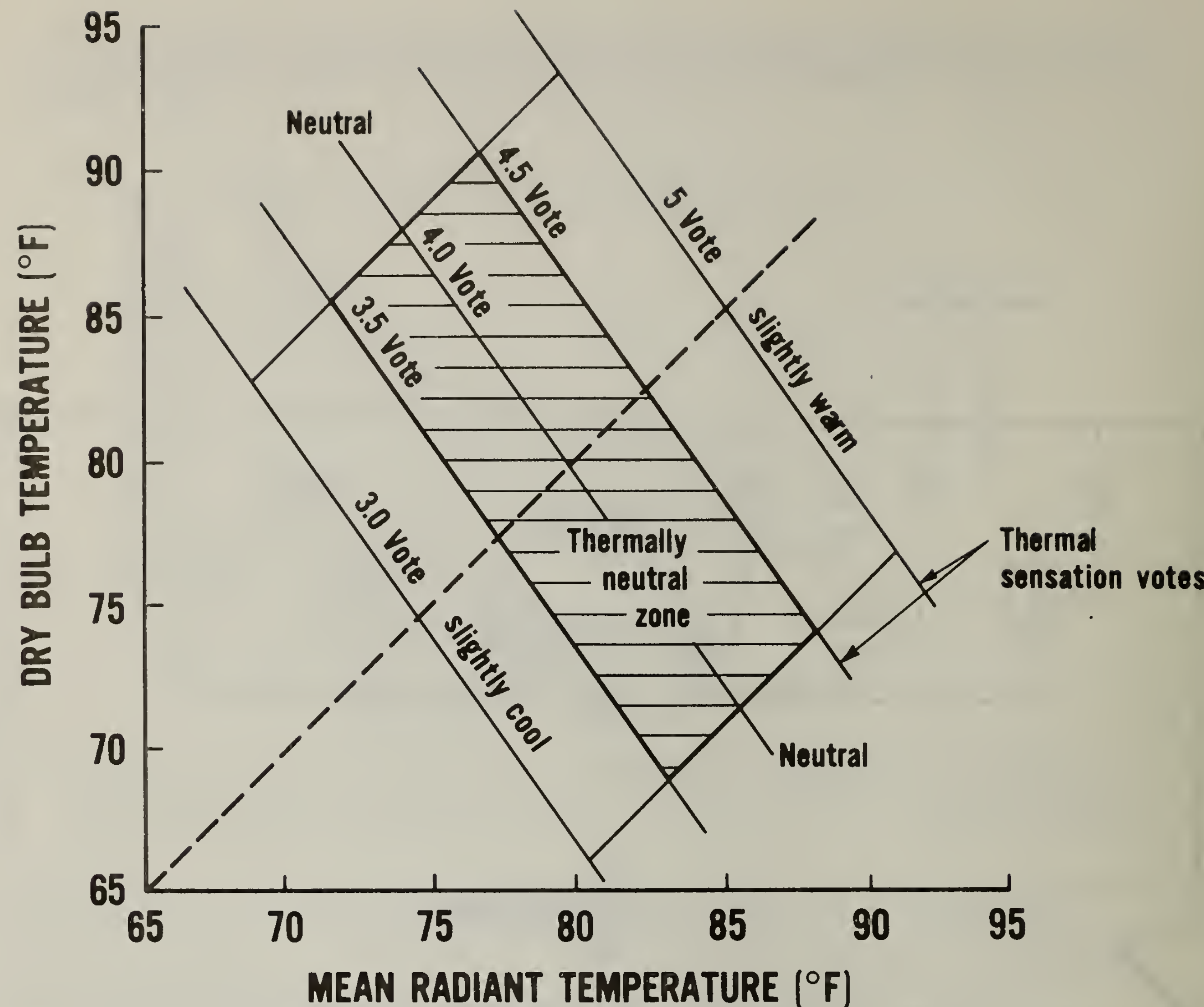

Figure 12. The thermally neutral zone proposed for sedentary subjects wearing clothes of insulation value about 0.6 clo in an environment with air velocity of 25-30 fpm and 4.35 in Hg vapor pressure. The allowable asymmetry of MRT is up to 12°F with a 0.2 shape* factor for the subjects. (Schlegel and McNall)

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* Tripp, W., Hwang, C. and Crank, R. "Radiation shape factors for plane surfaces and spheres, circles or cylinders." Kansas State Univ. Bulletin, Special Report No. 16, 46, (1962).

● Olesen, S. Fanger, P. O., Jensen, P. B. and Nielsen, O. J. "Comfort limits for man exposed to asymmetric thermal radiation." Proceedings of CIB Symposium on Thermal Comfort. London: Building Research Station, September 1972.

The purpose of this study was to estimate the limit of asymmetric thermal radiation to which people in thermal neutrality (where neither warmer nor cooler conditions are desired) can be exposed without feeling uncomfortable. Sixteen college age subjects (8 male, 8 female) participated in the study wearing minimal clothing (males -- underwear, females -- bikinis). Each subject was tested separately, starting in a condition of thermal neutrality, with wall temperatures being equal to the air temperature. Room conditions were systematically varied by decreasing the temperature of one wall in 5°C steps every half hour, while at the same time, the opposite wall temperature was increased by a like amount. Subjects were exposed to conditions where the cool wall was on one side, at the front, and finally toward the back. Water vapor pressure and air movement were kept constant throughout.

The major findings was that 50 percent of the subjects were able to sense the asymmetric radiation when the difference in radiant temperature between the two opposite walls was 7.4°C, independent of the direction faced.

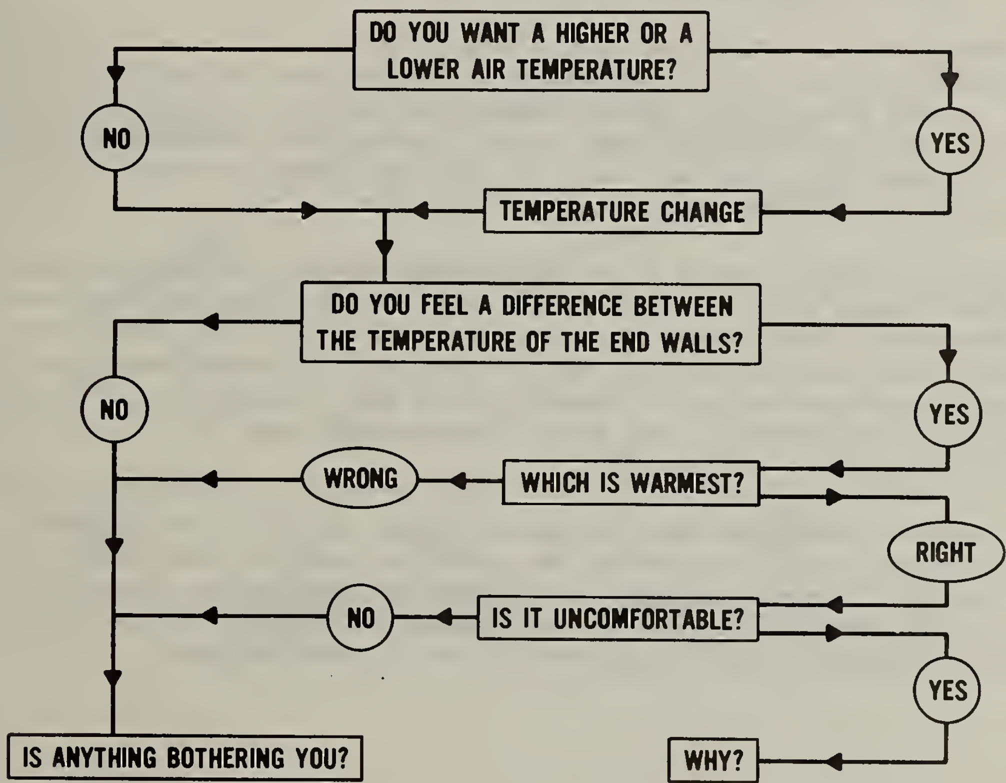

Figure 13. Questions for evaluating subjects' responses to asymmetric radiation. (Olesen, et al.)

- Michaels, K. B., Nevins, R. G. and Feyerherm, A. M. "The effect of floor surface temperature on comfort: Part KK, college age females." ASHRAE Transactions, 70, (1964).

Two series of studies were conducted to examine the effect of floor temperatures on comfort sensations. The studies differed from one another with respect to the activity performed by the subjects. In one case, subjects were seated and permitted to read or study school assignments. In the other condition, subjects stood and were occupied in writing and sorting bibliographic cards. Each subject was exposed to six different floor temperature conditions: 75, 80, 85, 90, 95, and 100°F (23.9, 26.7, 29.4, 32.2, 35, and 37.8°C), in a random order for a period of three hours. The air temperature was maintained at 75°F (23.9°C), and the air velocity was held to about 25 fpm or less throughout. The data collected from the subjects were skin temperatures and ratings from two ballots; one on thermal sensation using a 7 point scale and the other, a foot comfort scale (1-cold, 2-comfortable; 3-hot).

The findings indicated that under all conditions, floor temperature did affect foot comfort responses but not thermal sensation votes.

- Nevins, R. G. and Feyerherm, A. M. "Effect of floor surface temperature on comfort. ASHRAE Transactions, 73, Part 2: III.2.1. (1967).

This paper presents the findings in a research study which examined the effect of floor temperature on thermal sensation. Twenty-four subjects, 12 male and 12 female, served as subjects in the experiment, which took place in a test chamber. The subjects were clothed, seated, and at rest during the course of the study. Except for the floor surface, the remaining surfaces of the chamber were maintained at the same temperature as the air.

An experimental session lasted three hours, and thermal sensation votes and "foot comfort" votes were obtained at the end of the first hour and every 30 minutes afterward. Foot temperature data were also recorded throughout the study. Four test conditions were employed where floor temperature was varied and air temperature and relative humidity were kept constant at 75°F (23.9°C) and 40 percent respectively. The floor temperatures used were 60, 65, 70, and 75°F (15.6, 18.3, 21.1, and 23.9°C).

The study results indicated that the mean overall or whole body reaction was neutral to slightly cool, even when the subjects reported that their feet were "cool or "cold". Whether a person responding in this way is comfortable (satisfied with the environment) is uncertain. Male subjects responded to experimental conditions quite differently than female subjects.

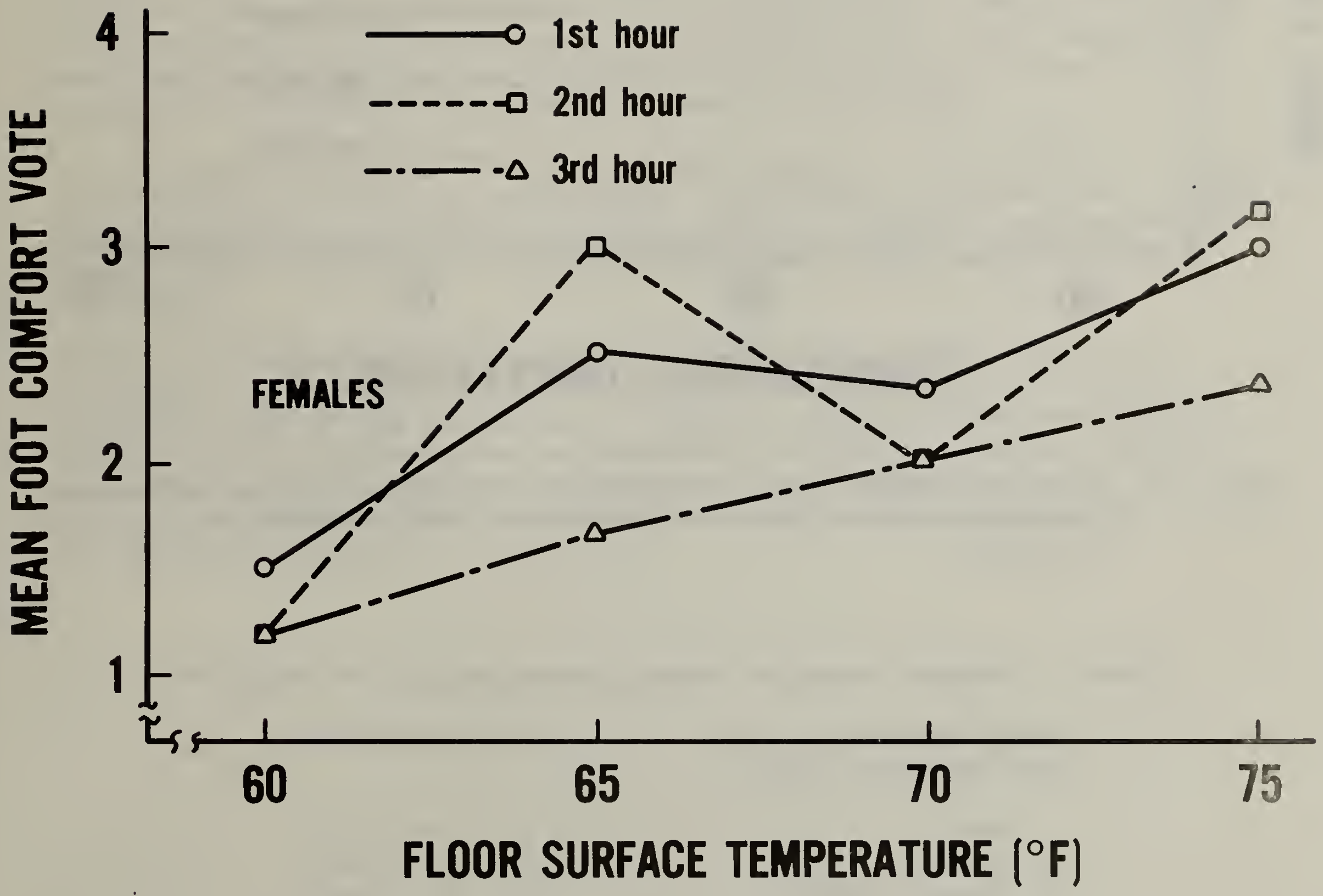

Figure 14. Mean foot comfort vote vs floor surface temperature for college-age males seated at rest, air temperature 75°F. (Nevins and Feyerherm)

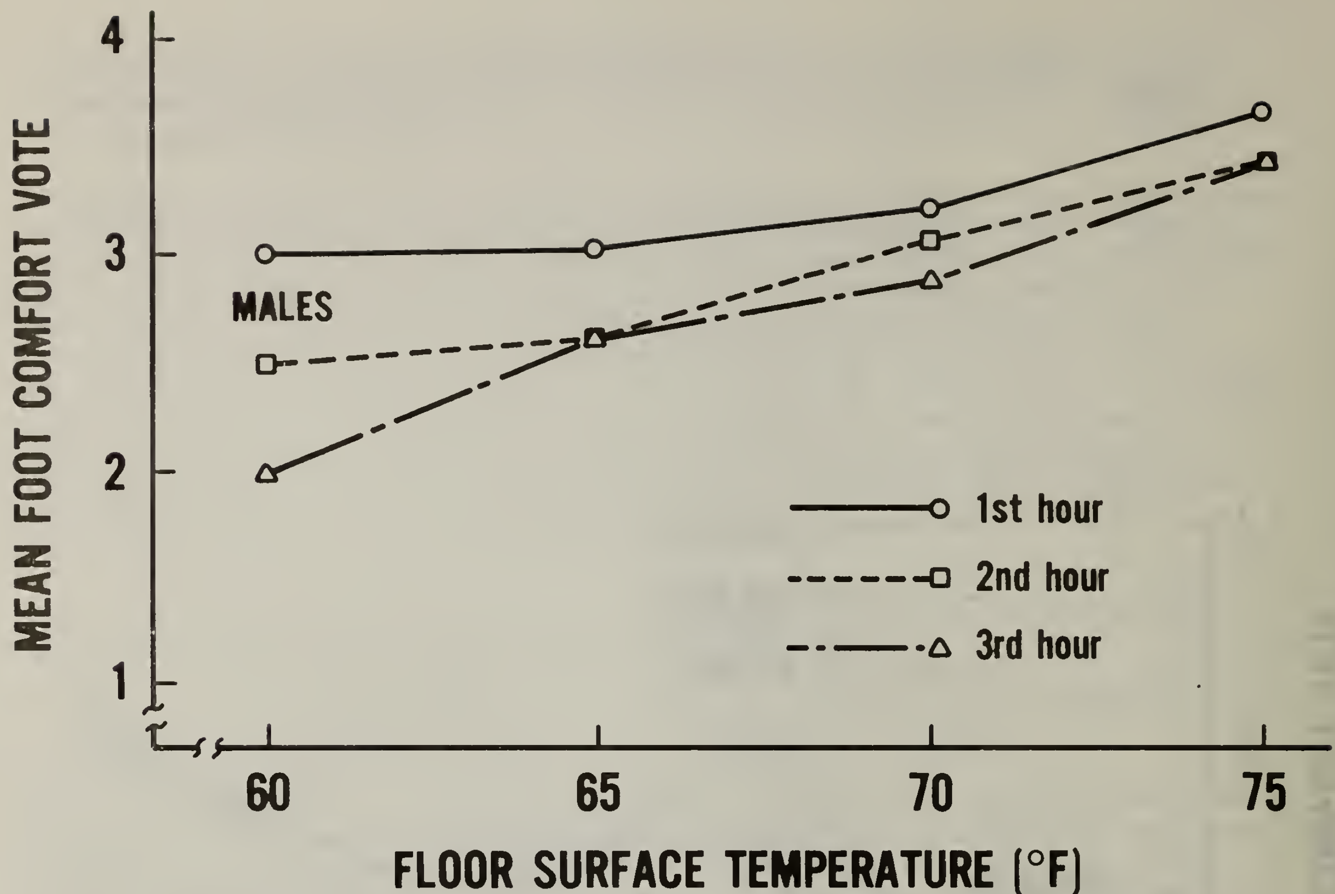

Figure 15. Mean foot comfort vote vs floor surface temperature for college-age females seated at rest, air temperature 75°F. (Nevins and Feyerherm)

Table 2. Thermal Sensation Voting Scales (Nevins and Feyerherm)

Thermal Sensation Vote (for the entire body)	Foot Comfort Vote
1. Cold	A. (1)* Cold
2. Cool	B. (2) Cool
3. Slightly Cool	C. (3) Neutral
4. Neutral	D. (4) Warm
5. Slightly Warm	E. (5) Hot
6. Warm	
7. Hot	

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* Number assigned for data processing.

• Fanger, P. O., Banhidi, L., Olesen, B. W., and Langkilde, G. "Comfort limits for heated ceilings" ASHRAE Transactions, 86, Part 2, V, (1980).

This experiment was conducted to determine the limits of overhead radiation which a person in "thermal neutrality" can be exposed without feeling discomfort. (Thermal neutrality is where neither higher nor lower ambient temperatures are desired.) While thermal neutrality is an important attribute of thermal comfort, another important factor is the absence of local warm or cool discomfort experienced on any part of the body. Overhead radiation can be the cause of such discomfort, and this relationship was explored in the present paper.

Eight male and eight female subjects served as subjects in the study, which lasted 3 1/2 hours. The subjects wore the standard KSU cotton twill uniform of 0.6 clo. The experiments took place in an environmental chamber, where the floor temperature was maintained at the air temperature. Skin temperatures were recorded during the study, as were rectal temperatures. Data recording equipment kept track of temperature changes in the chamber.

At the start of the study, the air and MRT were set at 25°C (72°F) -- estimated to be thermally neutral for most people. The subject was asked every 5 minutes throughout the study, whether any changes should be made in the temperature to achieve thermal neutrality, and then changes were made immediately when requested.

During the first hour of the experiment, the ceiling of the chamber was unheated. In the succeeding five half-hour periods, the subject was exposed to five different ceiling temperatures. When the ceiling temperatures were changed, the air temperatures were modified in order to maintain a constant operative temperature.* (See table below.) Every 5 minutes during the entire study the subject was asked about local thermal sensation in accordance with the procedure indicated in figure 16.

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* Operative temperature--approximately the average of the air and the mean radiant temperatures.

Table 3. Mean Values of the Air Temperatures Preferred by the 16 Subjects and the Corresponding Mean Values of the Ceiling Temperature, the Wall Temperatures, the Mean Radiant Temperature, and the Operative Temperature, During the Six Radiant Temperature Asymmetries.

Radiant Temp. Asymmetry K	Preferred Air Temp. °C	Ceiling Temp. °C	Mean Wall Temp. °C	Mean Radiant Temp. °C	Operative Temp. °C
0	24.1 ±1.6*	24.1	24.1	24.1	24.1
4.5	24.0 ±1.5	34	24.2	25.2	24.6
9.2	23.0 ±1.7	43	23.4	25.7	24.3
14.1	22.3 ±1.3	52	22.9	26.4	24.3
20.4	21.4 ±1.1	63	22.2	27.2	24.2
23.6	20.6 ±1.5	69	21.5	27.5	24.0

* Standard deviation of the sample.

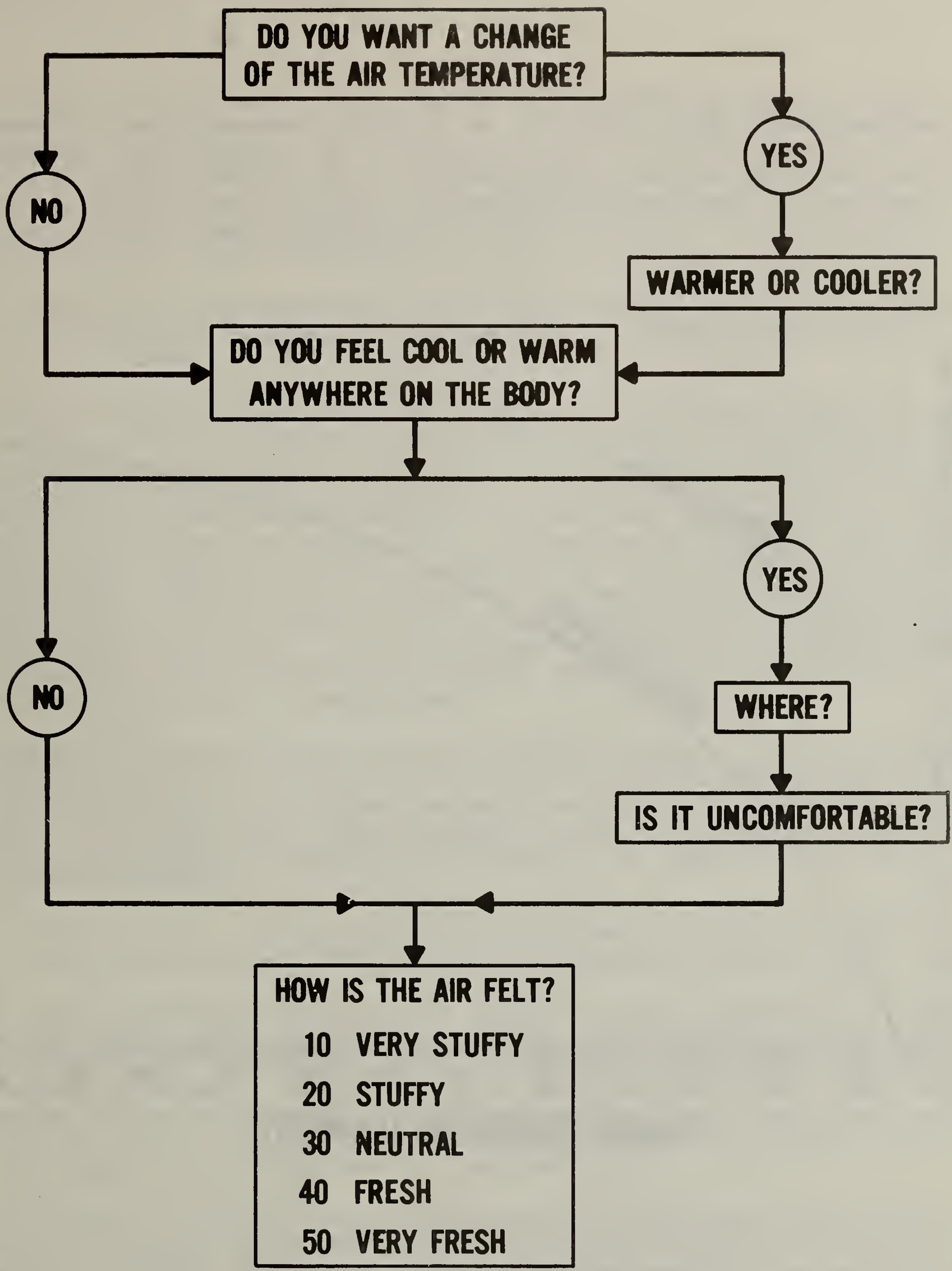

Figure 16. Procedure for asking the subjects about thermal preference, local thermal sensation, discomfort and freshness of the air. (Fanger, et al.)

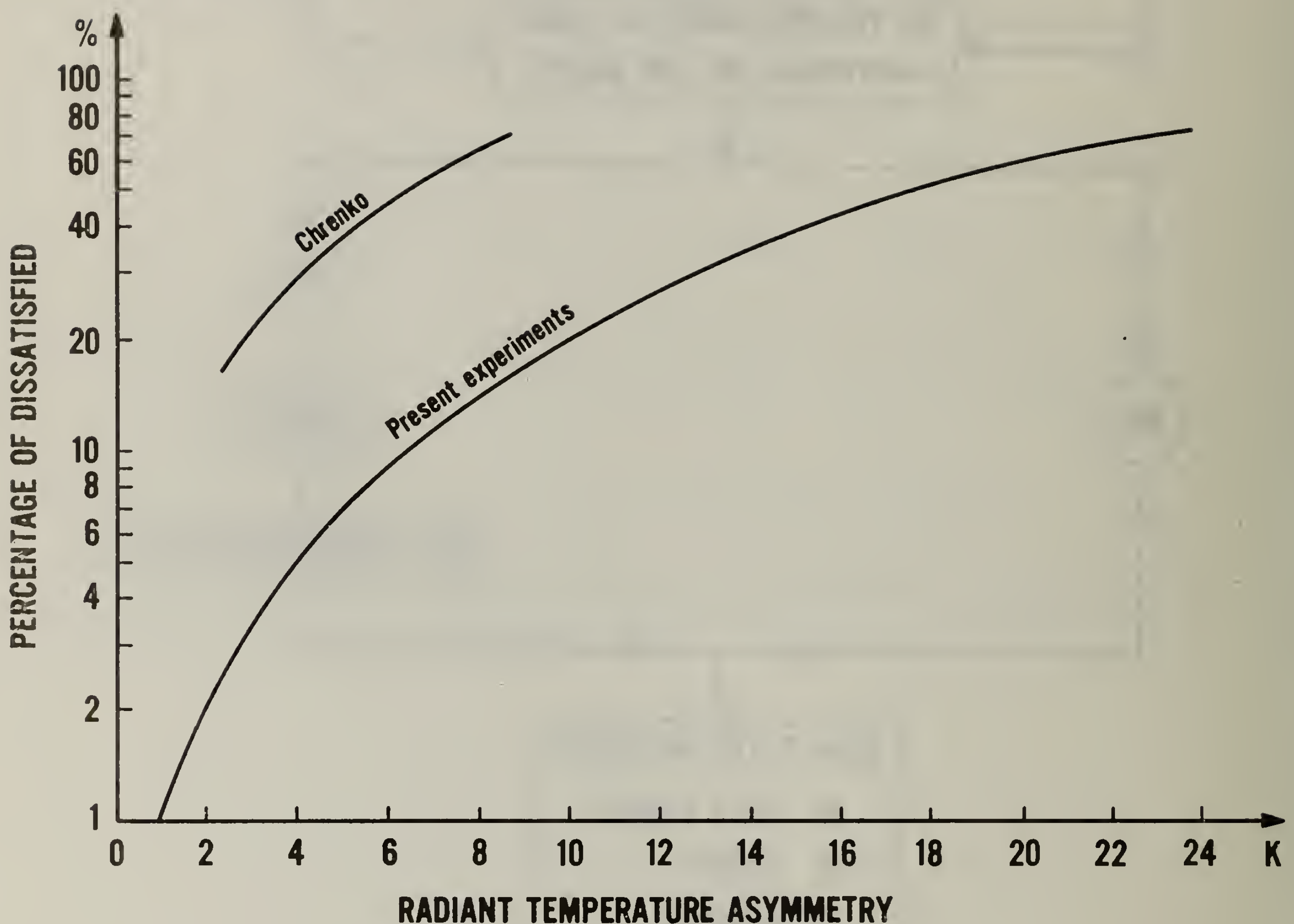

Figure 17. Percentage of people expressing discomfort due to overhead radiation as a function of the radiant nonuniformity expressed by the radiant temperature asymmetry. The corresonding curve by Chrenko (group B) is shown for comparison. (Fanger et al.)

The authors established a curve, showing the percentage of people feeling discomfort due to overhead radiation, as a function of the radiant temperature asymmetry. The curve applies to sedentary people who feel thermally neutral for the body as a whole. They recommend that a heated ceiling should not have radiant asymmetry exceeding 4K in spaces with high standards for the indoor climate. Under these conditions, less than five percent of the population are predicted to feel uncomfortable.

- McNall, P. E., and Biddison, R. E. "Thermal comfort sensations of sedentary persons exposed to asymmetric radiant fields." ASHRAE Transactions, 76, Part 1, (1970).

This paper describes a series of four studies in which radiant asymmetry was examined by using overhead or lateral exposure to heated or cooled panels to produce the physical conditions desired. Subjects were run in an experimental chamber and responded to the thermal conditions by completing ballots describing thermal comfort and thermal sensations. In the "cool wall" series of tests, one wall of the chamber was maintained at a temperature 20°F (-6.7°C) lower than the other chamber surfaces; the cool wall was at the side of the subjects (see figure 11). In the "hot wall" series, one side wall was maintained at 130°F (54°C), with the other room surfaces, at approximately the same temperature used in the "cold" series. The next studies used hot and cold ceiling panels; and finally a control condition was employed where surface conditions were uniform and equal to air temperatures.

Among the noteworthy findings were that thermally "neutral" subjects exposed to ceiling panels at 50°F (10°C) and 130°F (54°C), and wall temperatures of 50°F (10°C) experienced no significant discomfort attributable to asymmetric radiation. On the other hand, similar subjects exposed to wall panels at 130°F (54°C) did experience discomfort attributable to the asymmetry of the mean radiant temperature.

- McIntyre, D. A. "Overhead radiation and comfort." Electricity Council Research Centre Report R918, Capenhurst, Chester CH1 6ES, May 1976.

The report describes a series of five studies to better understand the effects of asymmetrical radiation on thermal comfort. The investigations were designed to systematically vary ceiling and wall temperatures to determine the effects on experimental subjects. Subjects sat in an environmental chamber for 45 minutes, reading, talking or engaging in other sedentary activities. After this acclimatization period, they rated their thermal sensations on a seven point scale which ranged from "much too warm" to "much too cold".

In the first two studies, the air temperature and mean radiant temperatures were kept constant, while ceiling temperatures were high, and wall temperatures were low. Subjects felt cooler in the hot ceiling condition than under uniform heating. The other studies "fine tuned" some of the experimental procedures used in the first two studies -- e.g., varying the size of the panels, and tested the degree of asymmetry acceptable to subjects. The concept of radiation vector (from illumination theory) is also introduced, which permits radiation to be described in any required detail.

2.4 AIR MOVEMENT

The importance of air movement as a major factor in feelings of thermal comfort is attested to by the early studies of this variable. Houghton, et al., examined the effects of localized air movement on skin temperature and feelings of warmth. McIntyre examined preferred air speeds needed for thermal comfort in warm conditions. Azer, et al., examined sensory votes and associated physiological responses to localized ventilation in hot environments. McIntyre, in a later study, examined air speed as an independent variable in an investigation of thermal comfort.

- Houghton, F. C., Gutberlet, C. and Witkowski, E. "Draft temperatures and velocities in relation to skin temperatures and feelings of warmth." ASHVE Transactions, 44, (1938).

This paper investigates the effects of localized air movement (on the neck or the ankles) on skin temperature and feelings of warmth. Subjects sat in an experimental room under uniform temperature of 70°F (21.1°C) and 50 percent humidity conditions with general air velocity from 15 to 25 fpm. They had air streams of various velocities and temperatures directed at the back of the neck or at the ankles. Observations were made on ten male subjects of skin temperatures of the affected part of the body, and sensations of "coolness" or "comfort", on a seven point scale. Draft temperatures were varied from 70 to 65°F (21.1 to 18.3°C) and air velocities from 0 to 110 fpm.

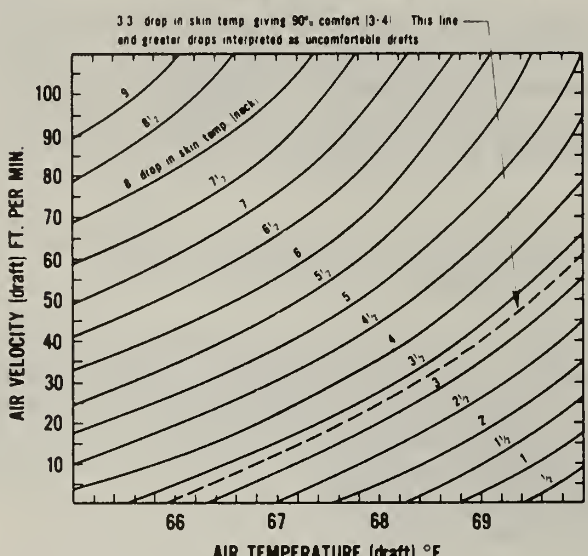

Figure 18. Relation between the temperature and velocity of a draft and the drop in skin temperature of the neck. Skin temperature drop of 3.3 degrees and greater interpreted as objectionable draft.

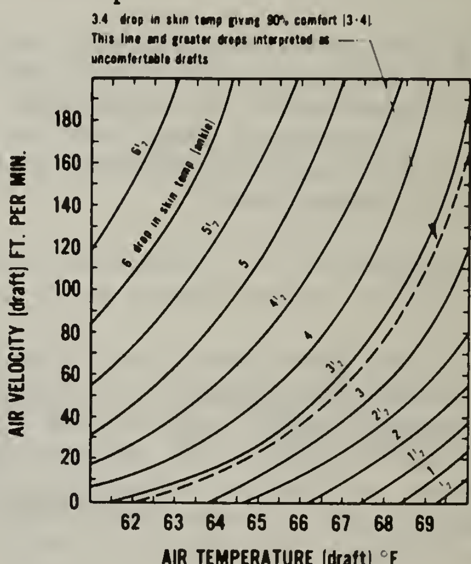

Figure 19. Relation between the temperature and velocity of a draft and the drop in skin temperature drop of the ankle. Skin temperature drop of 3.4 degrees and greater interpreted as objectionable draft.

- McIntyre D. A. "Preferred air speeds for comfort in warm conditions." Electricity Council Research Centre Report N1111, Capenhurst, Chester Chl 6ES, January 1978.

This experiment examined the effect of air movement on comfort sensations in warm conditions. Eleven subjects were exposed to five different temperature conditions from 22° to 30°C, at 2°C intervals. The subjects were run individually in an environmental chamber equipped with an overhead fan that could be adjusted to a setting which produced maximum comfort. At half hour intervals, the subjects filled out a questionnaire describing their comfort feelings. In addition, every 15 minutes they were asked to adjust the speed of the fan. Skin temperature readings were also collected.

The experimental findings indicated that fan speeds were selected which increased as a function of temperature. However, when the temperature reached 30°C, overall thermal comfort decreased despite high fan speed.

- Azer, N. Z., Nevins, R. G., Olesen, S. and Leug, H. C. "Improvements in sensory votes and their associated physiological responses by localized ventilation in hot environments." Proceedings of CIB Symposium on Thermal Comfort. London: Building Research Station, September 1972.

This experiment investigated the effects of localized ventilation on thermal comfort and physiological responses. Three groups of six subjects were subjected to an air stream to the front of the head, in a hot environment. They were dressed in a standard uniform (0.6 clo) and participated in a two tasks; the central task was the tracking of a target while the peripheral task was one of visual search. One group was tested in a 32.2°C and 71 percent RH environment, the second in a 35°C and 50 percent RH enviroment, and the third group under conditions of 37.8°C and 34 percent RH. The three conditions are equivalent to an Effective Temperature of 29.3°C. Subjects performed under two conditions, one with localized ventilation, and the other, without it.

The ventilation outlet was located 40 cm from the subjects face, and had a 10°C temperature and a velocity of 3.8 m/s.

The local ventilation resulted in a change in comfort votes in the direction of thermal neutrality and greater comfort. (See below.)

- McIntyre, D. A. "An investigation into the effect of low speed air movement over the body." Electricity Council Research Centre Report M 1262, Capenhurst, Chester, CH1 6ES, U.K., Nov. 1979.

This study was concerned with the effect of air movement on thermal comfort. Twelve female typists served as subjects in an investigation which was conducted on three consecutive days -- consisting of six, three hour experimental sessions. The subjects wore light summer dresses (estimated at .5 clo) throughout the study. During the first hour of the experiment each subject had the opportunity to have the temperature adjusted to "optimum" conditions -- by requested temperature changes at 15 minute intervals. At half hour intervals, subjects responded to a questionnaire evaluating thermal conditions. Following the

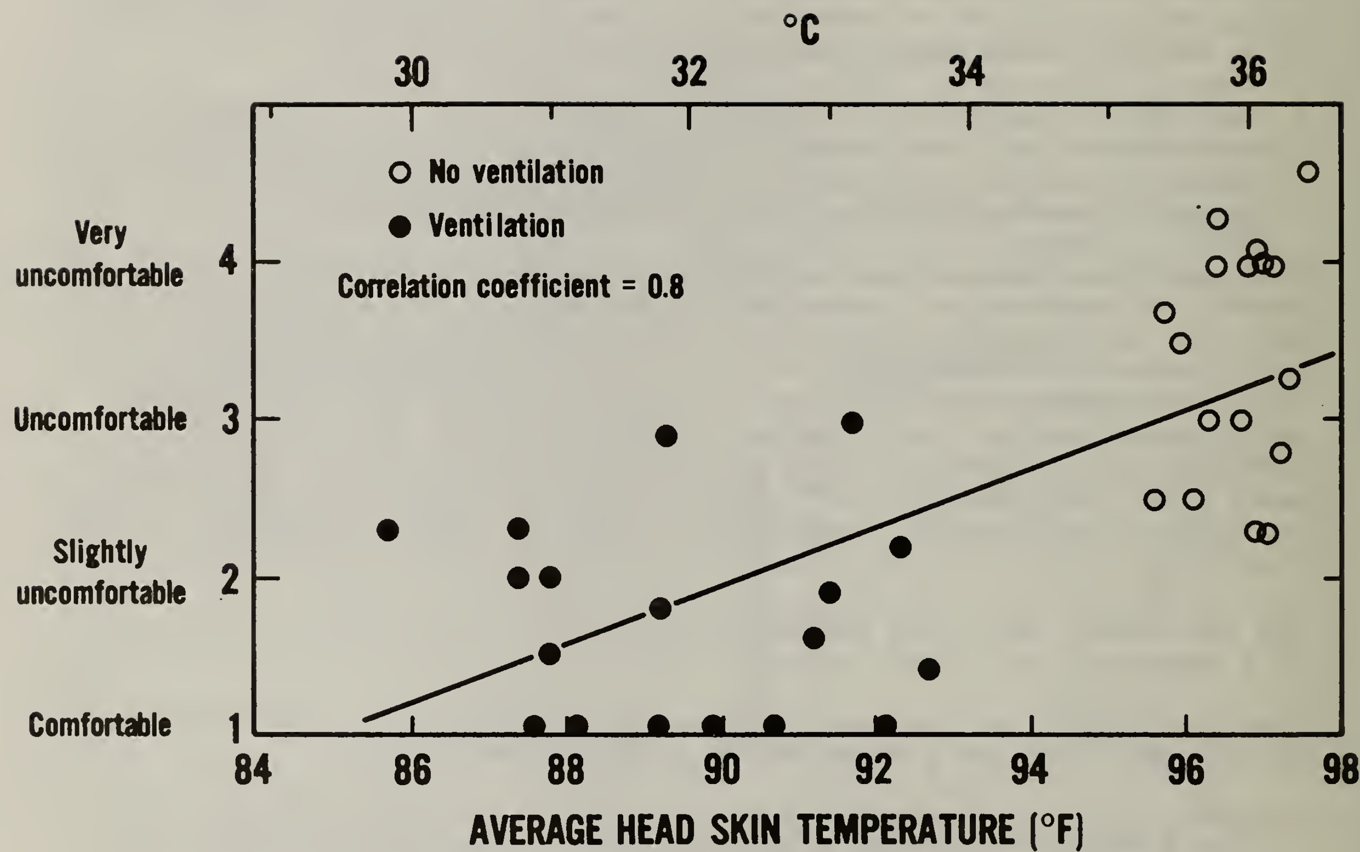

Figure 20. Variation of comfort sensation with average head skin temperature comfort. (Azer, et al.)

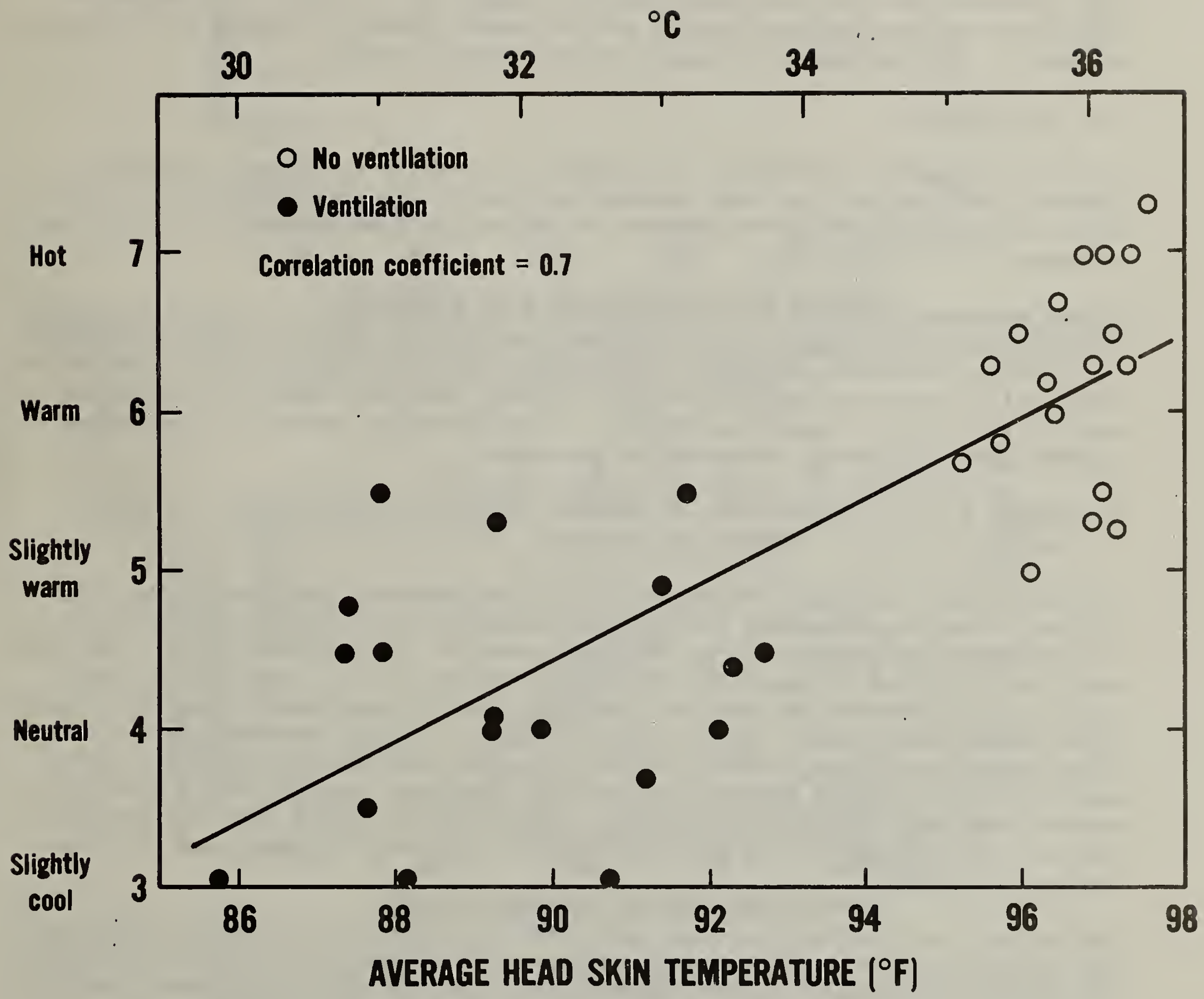

Figure 21. Variation of thermal sensation with average head skin temperature--thermal sensation. (Azer, et al.)

first hour, lighting conditions were systematically varied for three half hour periods, while subjects engaged in a variety of visual tasks.

The major independent variable being manipulated was air speed. Four different air speeds were examined -- less than 0.1 m/s, 0.15, 0.25 and 0.35 m/s. Under these conditions, subjects could not reliably detect air movement, even at the highest air speed tested. The author hypothesizes that these results might be attributable to: (1) the steadiness of the air flow, and (2) the relatively high temperatures that were selected as optimums (24 - 25°C). The subjects reported their feelings on several scales, which showed no effect of air speed on comfort, nor evidence to suggest an optimum air speed.

2.5 ACTIVITIES

While environmental conditions in buildings importantly influence thermal comfort, they are not the only determining factor for this condition. Another major influence is the strenuousness of the activity engaged in by a building occupant.

Fanger examined activity level (performance in a step test) in terms of thermal comfort, mean skin temperature, and sweat secretion. McNall et al., performed two studies to obtain metabolic rates at four activity levels, and to determine their relationship to thermal comfort. Rohles and Konz examined a different kind of activity -- showering behavior -- to determine optimal air and water temperatures for energy conservation purposes.

- Fanger, P. O. "Calculation of thermal comfort, introduction of a basic comfort equation". ASHRAE Transactions, 73, Part II, (1967).

This study was performed to determine skin temperatures and sweat rates for college students performing at four different activity levels. The activity performed was the modified step test described in the next reference. The students were clothed in standard cotton uniforms (0.6 clo). For each activity level the air temperature was maintained at the optimum level found in the previously mentioned study. The relative humidity was kept constant at 45 percent. Skin temperatures were measured at the locations indicated in figure 7. The mean value of the skin temperature over the last half hour of the 3 hour test session was used for all calculations. The activity levels were achieved by varying the step-rest cycle for the subjects. Figure 22 summarizes the skin temperature data.

The author also studied the sweat secretion under the four activity conditions and utilized the data for subjects in thermally neutral conditions in reference 48. Fanger concluded from his findings that the sensation of thermal comfort is closely related to the mean skin temperature and sweat secretion data. A thermal comfort equation was then derived, based on these data and the findings of other relevant thermal comfort studies.

- McNall, P. E., Jr., Jaax, J., Rohles, F. H., Nevins, R. G. and Springer, W. "Thermal comfort (thermally neutral) conditions for three levels of activity." ASHRAE Transactions. 73, Part I, (1967).

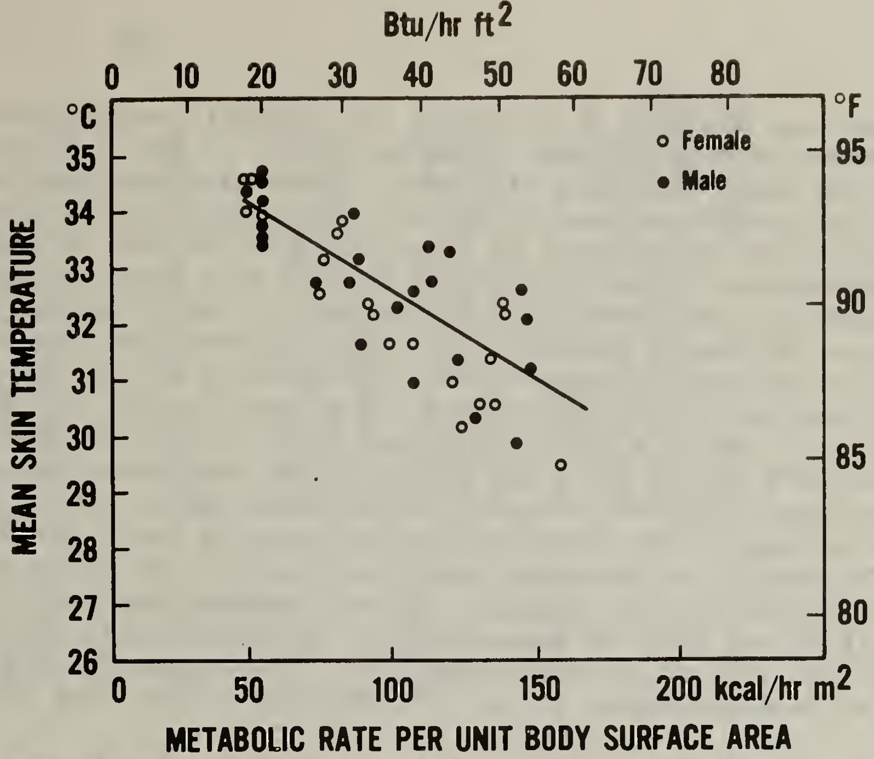

Figure 22. Mean skin temperature as a function of the metabolic rate per unit body surface area for persons in thermal comfort. (The line represents a linear regression). (Fanger)

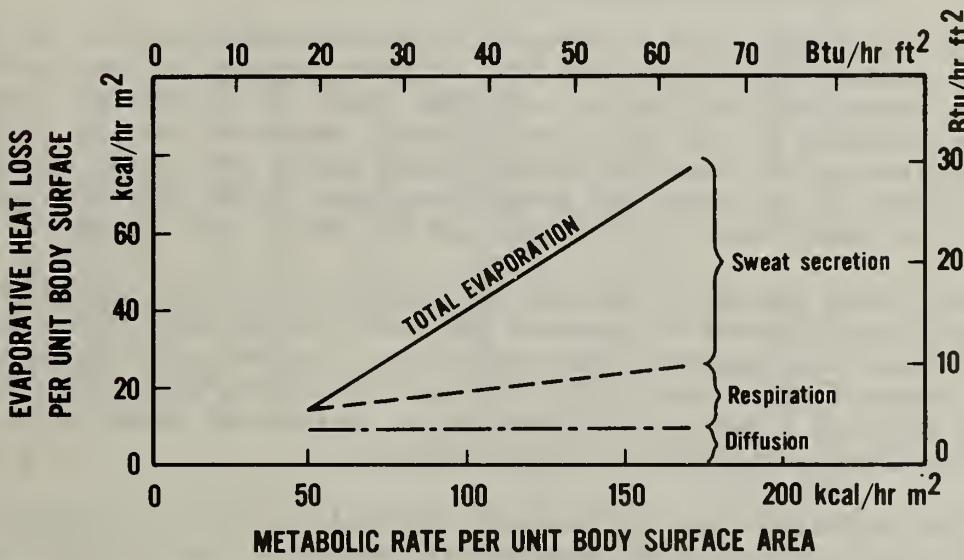

Figure 23. Evaporative heat loss per unit body surface as a function of the metabolic rate per unit body surface area for persons in thermal comfort.

(The solid line is the linear regression line for total evaporation heat loss. The dashes and the broken lines show respectively the calculated total insensible perspiration heat loss and the diffusion heat loss.) (Fanger)

This experiment was designed to determine the thermally neutral temperature and zone for subjects working at three different levels -- 600, 800, and 1000 Btuh. Four hundred and twenty subjects (210 male, 210 female) took part in the study wearing standard cotton uniforms (0.59 clo). For each activity level the subjects were studied under three RH conditions (25, 45, and 65 percent) under different temperatures. The temperatures studied were those recommended in the ASHRAE Guide and Data Book, with the central of three temperatures being that defined as "thermally neutral". The other temperatures were 6°F (3.3°C) above and below the central temperature. For the high activity level, the temperatures were 54, 60, and 66°F (12.3, 15.6, and 18.9°C); for the medium activity — 60, 66 and 72°F (15.6, 18.9, and 22.2°C); and for the low activity -- 66, 72, and 78°F (18.9, 22.2, and 25.6°C). The task performed was walking on two 9 inch steps, with the activity levels being varied with respect to the ratio: time walking: time standing (low 25:5; medium 10:5; low 5:5 (in minutes). The results of the study indicated that for the metabolic rates of 600, 800, and 1000 Btuh, the thermally neutral temperatures were 72, 66, and 60°F (22.2, 18.9, and 15.6°C), respectively. Relative humidity had little effect on thermal comfort,for most conditions. The single exception was reduced performance by female subjects at the 1000 Btuh rate under high humidity conditions.

- McNall, P. E., Ryan, P. W., Rohles, F. H., Nevins, R. G., and Springer, W. E. "Metabolic rates at four activity levels and their relationship to thermal comfort." ASHRAE Transactions, 74, Part 1, IV 3.1, (1968).

The present experiment is a followup to an earlier investigation of thermal comfort conditions for college age men and women engaged at four levels of activity: sedentary; low, medium, and high (ratio of walking and standing). The primary purpose of the study was to obtain empirical data on the heat production (metabolic rates) of healthy young people performing at different activity levels -- to verify the predictions made in the earlier study. Table 4 summaries the conditions of the study, and the conditions simulated.

The subjects were exposed to thermal conditions for 3 hours in groups of five. All subjects were dressed in standard KSU cotton twill uniforms of 0.59 clo. Metabolic rates were measured after each hour. The sedentary study was performed at three temperatures, 66°, 72°, and 78°F (18.9, 22.2, and 25.6°C). The other activity levels were studied in an environment found to be thermally neutral for these activities in earlier studies.

The results indicated that the sedentary metabolic rate was independent of temperature over the range of temperatures examined. The 3 hour sedentary mean metabolic rates for all three temperatures were 389 and 301 Btuh for the males and females, respectively. The three-hour mean metabolic rates for the low, medium, and high levels of activity were 662, 829, and 1061 Btuh, respectively for the male subjects and 492, 653, and 826 for the female subjects.

Table 4. Subjects, Temperature, Activity Level, Expected Metabolic Rates, and Corresponding Activities and Occupations of This Study

Number of Subjects	Temperature (F) Humidity (rh)	Experimental activity	Expected metabolic rates (Btuh) Males	Expected metabolic rates (Btuh) Females	Activities and Occupations
20	66/50	sedentary-sitting quietly	375-425	290-340	
30	72/50	sedentary-sitting quietly	375-425	290-340	sitting at rest, reading, writing
20	78/50	sedentary-sitting quietly	375-425	290-340	
	72/45	low: walk 5 min/ stand 25 min	600-650	475-525	slow movement about a room, driving car in traffic, typing rapidly
20*	66/45	medium: walk 5 min/ stand 10 min	800-850	650-700	vehicle repairs, shoemaker walking (3 mph), moderate work at machine or bench
	60/45	high: walk 5 min/ stand 5 min	1000-1050	800-850	washing, heaving ironing, carpenter, stone and mason work, walking about with moderate lifting or pushing metal worker and industrial painter

* The same subjects were used at all three activity levels.

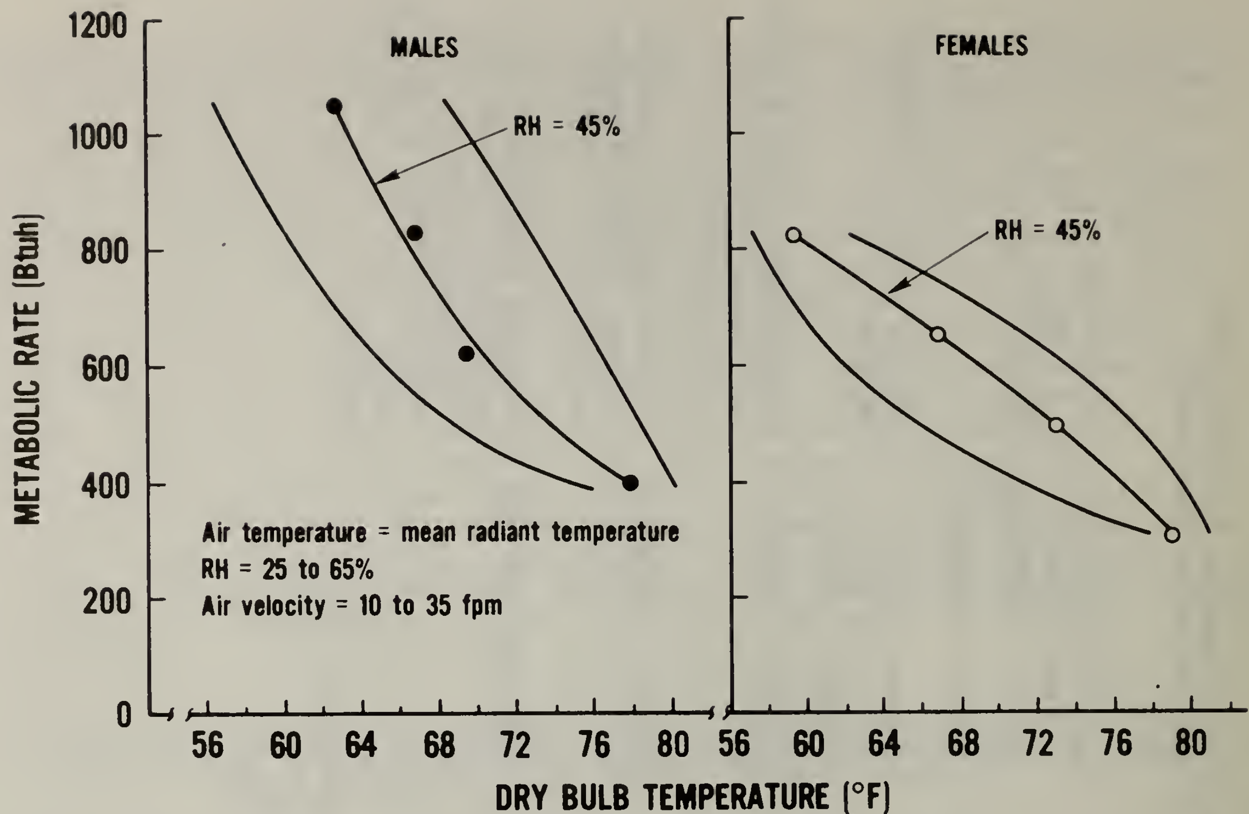

Figure 24. Proposed thermal comfort zone as a function of metabolic rate for average college-age males and females. (McNall, et al.)

- Rohles, F. H. and Konz, S. A. "Showering behavior: implications for water and energy conservation," ASHRAE Transactions, v. 88(1), (1982).

To be successful solar water heating systems must be able to meet the hot water needs of the occupant. This paper gives the water temperature preferences for showers.

Three groups of subjects were selected to determine the amount and temperature of the water used when showering. The control group of 120 subjects (60 men and 60 women) was divided into four groups (15 men and 15 women) who, after showering, dressed in rooms whose temperatures were 18.3°C (65°F), 21.1°C (70°F), 23.9°C (75°F), and 26.7°C (80°F). The greatest amount of comfort after showering was experienced in the 26.7°C (80°F) room. This group, who did not wash their hair while showering used a mean of 36 liters (9.2 gal) of water for their showers. A second group of subjects (12 men and 12 women), who did wash their hair, used 62 liters (16.4 gal); this represented an increase in water use of 78 percent. A third group (12 men and 12 women), who had their showers fitted with a shower head that restricted the flow-rate of water, used 24 liters (6.4 gal) or 30 percent less water. However, they set their water temperature at 41.1°C (106°F) vs the 38.9 (102°F) setting of the other two groups. Implications of these findings are discussed in relation to both water and energy conservation.

3. FIELD STUDIES OF THERMAL COMFORT

As we noted earlier, laboratory studies are favored by most researchers because of the experimental control available to investigators. However, all laboratory findings must be validated under realistic field conditions. Furthermore, many pertinent variables can only be identified in field situations, e.g., social and institutional ones. Field research studies of thermal comfort have been performed for both of these purposes.

Loudon examined summertime temperature conditions in buildings without air conditioning. Humphreys and Nicol investigated the thermal comfort of office workers performing their usual jobs. Langdon and Loudon conducted a social survey of schools in summertime. Wanner surveyed environmental conditions in offices and in a lecture theater. Humphreys collected and compared findings obtained in more than 30 field studies of thermal comfort. Gagge and Nevins conducted a field study of the energy conservation guidelines established by the Federal Energy Administration. Finally, Towle described the findings obtained in a survey of passive solar residences.

- Loudon, A. G. "Summertime temperatures in buildings without air-conditioning." Building Research Establishment Current Paper 47/68, May 1968.

The paper describes a method of calculating summertime temperatures based on a variety of parameters which include: solar radiation intensities, solar gain factors for glass, blinds and other sun controls, and admittances of building components--methods of smoothing out diurnal temperature swings experienced in a building.

Experimental findings are presented which show agreement with predicted temperatures in unoccupied buildings. Predicted peak temperatures in occupied buildings of two types (schools and offices) were compared with user comments on thermal conditions obtained during social surveys.

- Humphreys, M. A. and Nicol, J. F. "An investigation into thermal comfort of office workers." Journal of the Inst. of Heating and Ventilating Engineers, 38, Nov. 1970.

This study was a field investigation of thermal comfort. The subjects were members of the British Research Station who continued in their everyday tasks while serving as subjects. Each participant had an automatic environmental monitor on the desk, which recorded globe temperatures, air velocity, wet bulb and dry bulb temperatures. The devices also enables the subjects to record comfort votes at regular intervals. The monitors were all connected to a central data logger, which controlled their operation and produced a punched paper tape -- to be read by a computer.

The study findings indicated that simple measures of globe temperature were found to be as closely related to comfort sensations as complex environmental measures. The results suggest to the authors that comfort data can be used to estimate permissable temperature variations -- not predict an optimum temperature.

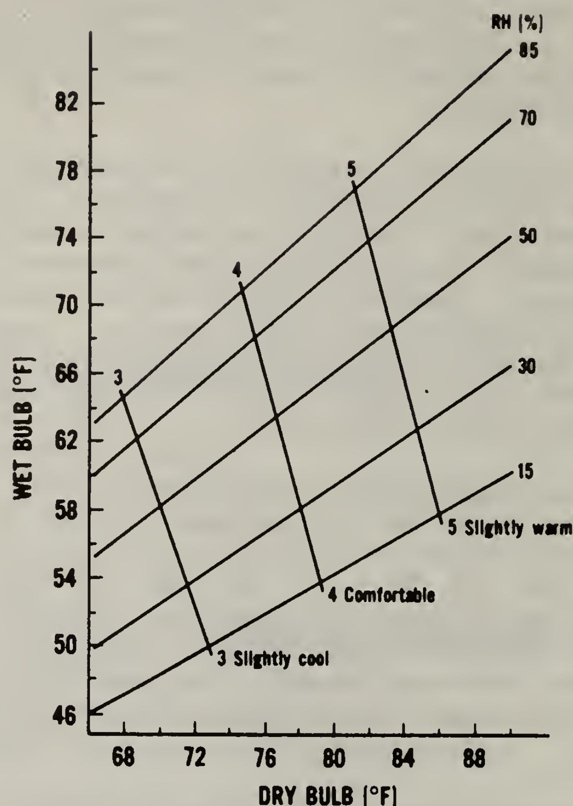

Figure 25. Lines of thermal sensation for men and women combined, after a three hour test exposure. (Humphreys and Nicol)

- Langdon, F. J. and Loudon, A. G. "Discomfort in schools from overheating in summer." The Journal of the Institute of Heating and Ventilating Engineers, 37, (1970).

A social survey was carried out in 77 school buildings in which teachers were asked to report their experiences of summer overheating. In conjunction with the survey, information was collected concerning the structural and design characteristics of the school buildings by site visits and the analysis of drawings. The object of the study was to determine the design characteristics of the buildings that were responsible for reported thermal discomfort.

The principal factors identified with thermal discomfort were orientation, whether windows provided cross ventilation, structural weight, and the occurence of external noise.

- Wanner, H. U. "Comfort and air quality in air conditioned rooms" in Thermal Comfort and Mode Rate Heat Stress. BRE Rpt. 2, Garston, Watford, U.K., 1973.

The author conducted a field study in offices and a lecture theater. In conjunction with a ballot consisting of three choices (do you find the temperature in this room at this moment, agreeable, too cold, too warm?), measurements of the environment were taken. They included temperature, humidity, and air movement. He examined 122 air conditioned and 189 nonairconditioned offices with 1172 people, during summer and winter seasons. Also, 667 students attending classes in a lecture theater were questioned in the winter and 1093 in the summer.

In the offices, the majority of respondents judged temperatures of over 24°C in the summer as "too warm". Seventy percent of the students in the theater described temperatures between 20.3 and 21.7°C as "just right" in the winter season. As temperature increased, despite relative humidity of 50 percent, more and more subjects rated the air as "too dry".

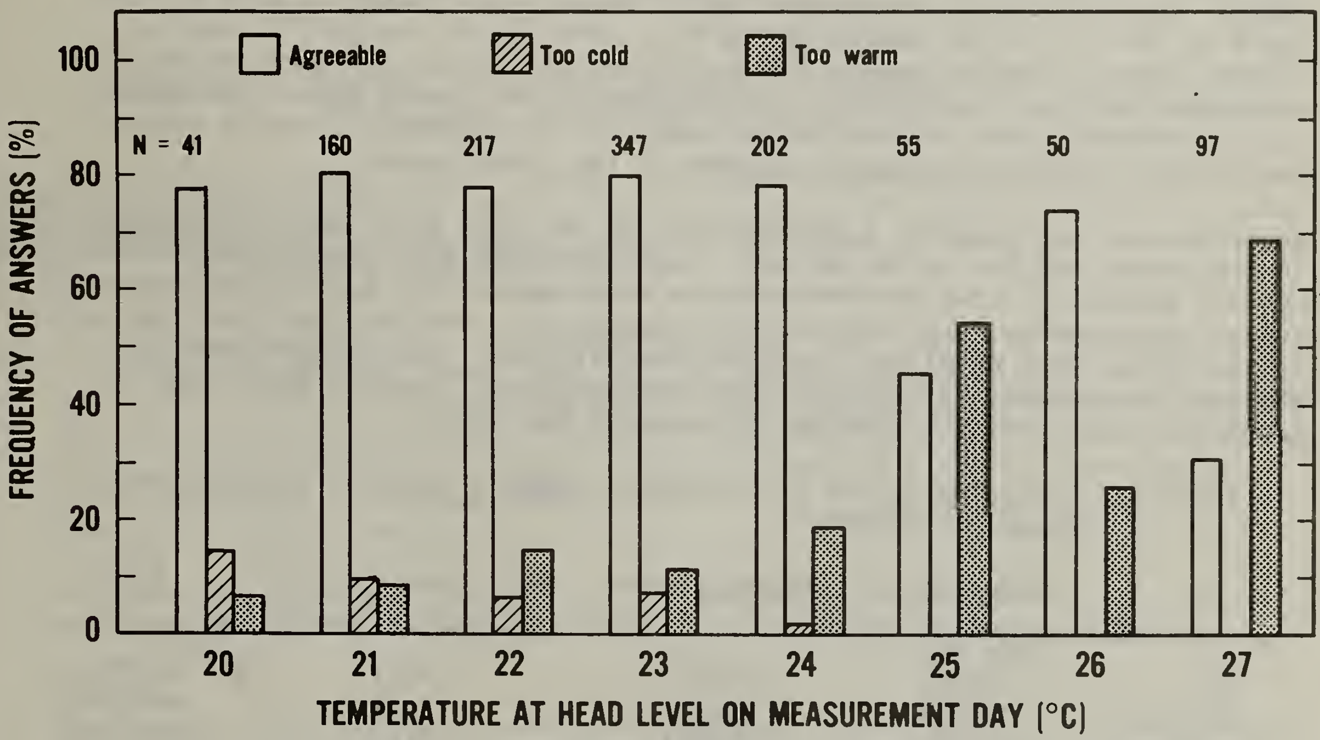

Figure 26. Subjective assessments of air temperatures. (Wanner)
N = Number of people questioned at each degree of temperature = 100%
Altogether 1172 measurements and answers

- Humphreys, M. A. "Field studies of thermal comfort compared and applied." Building Research Establishment Current Paper 76/75, Garston, Watford, U.K., August 1975.

Data from more than 30 field studies of thermal comfort are collected and tabulated in this report. Together they comprise over 200,000 observations made in a variety of climates. The methods of study and analysis are critically described. A comparison is made of the performance of thermal indices and subjective rating scales, the temperature for thermal neutrality, and the variability associated with these rating schemes. The conclusions of the field studies are compared with studies conducted in climate chambers and with thermal comfort modelling efforts. A new method of estimating the median warmth response is presented.

- Gagge, A. P., and Nevins, R. G. "Effect of energy conservation guidelines on comfort, acceptability and health" in Thermal Analysis -- Human Comfort -- Indoor Environments, Ed. Mangum, B. W. and Hill, J. E., NBS Spec. Pub. 491, Sept. 1977.

A field study was conducted during summer and winter seasons to evaluate the energy savings guidelines established by the Federal Energy Administration (FEA). The guidelines established indoor temperature limits of 68°F to 70°F (20°C to 21.1°C) in the winter and 78°F to 80°F (25.6°C to 26.7°C) for the summer season. (Unfortunately the study conditions actually examined did not correspond to these guidelines. In the case of the summer study, the weather was unseasonably cool; in the winter study the environmental control system was faulty, preventing adequate control of the temperatures.)

The study was performed in a GSA building in New York City, with 230 respondents in the summer and 262 in the winter. Questionnaires were distributed to obtain comfort sensation votes and measurements were made of dry and wet bulb temperatures, air movement, and Black Globe temperatures. Estimates of clothing insulation values were obtained from questionnaire data. The comfort data and physical measurement information were then analyzed. Table 5 and figure 27 summarize representative findings obtained in the study.

Table 5. Cross-Tabulation of Findings: Comfort Sense vs Air Temperature (Gagge and Nevins)

T_a	Comfortable	Uncomfortable	Very Uncomfortable	Total
	Row (%)			
22.5	37(60)	22(35)	3(5)	62(100)
22.5-22.9	71(76)	19(21)	3(3)	93(100)
23.0-23.4	67(72)	25(27)	1(1)	93(100)
23.5-23.9	31(62)	18(36)	1(2)	50(100)
24.0-24.4	22(67)	9(27)	2(6)	33(100)
24.5-24.9	27(59)	18(39)	1(2)	46(100)
25.0-25.4	9(69)	2(15)	2(16)	13(100)
25.5	0	0	0	0
Col. Total (% Total)	264(68)	113(29)	13(3)	390

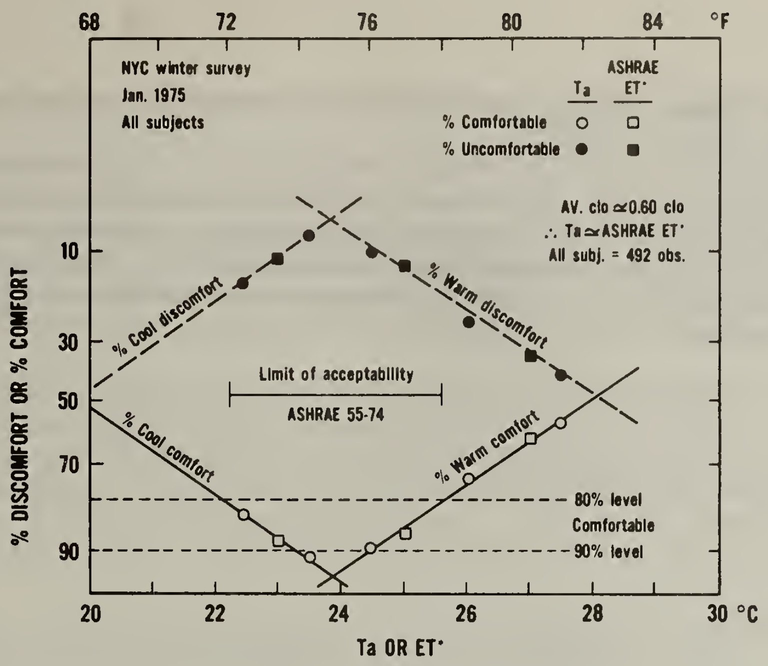

Figure 27. Percent comfort-uncomfortable sensation vs T_a on probability coordinates. (Gagge and Nevins)

Both the summer and winter findings were consistent with the recommendations of ASHRAE Standard 55-74 in that at least 80 percent of normally clothed men and women indicated that they were thermally comfortable at temperatures between 72 and 78°F ET (22.2 to 25°C).

The authors indicate that the guidelines might be extended by modifying the guidelines in the following ways: In the summer, the upper level may be extended to 80°F (26.7°C) by the use of light clothing (less than 0.4 clo), by increasing air movement above 50 fpm, by lowering the relative humidity, or by doing a combination of the above. In the winter, 68°F (20°C) can be made acceptable if the clo value is increased to 0.9 - 1.2, provided the legs and feet are properly covered.

- Towle, S. "User evaluation study of passive solar residences. (SERI/TO-63-350). Golden, Colorado: Solar Energy Research Institute, March 1980.

This paper describes the preliminary findings of a survey of user experiences with passive solar homes. Owners and builders of passive solar homes were interviewed concerning their personal experiences. The study was conducted in the spring of 1979. Residents of 21 passive solar homes built speculatively or judged to be adaptable to mass market appeal were the subjects of the study. The market value of the homes ranged from $25,000 to $100,000. The survey consisted of in-depth interviews of the respondents.

The passive system solar types ranged from nine direct gain systems, six isolated gain systems, four earth bermed homes with some direct gain and one sample home from several other types, e.g., solarium, underground. Conventional backup systems were used to keep the homes at a constant temperature -- usually between 68 - 70°F (20°C - 21.1°C).

Occupants noted that location, price and design were major reasons to purchase home, rather than the fact that it had a passive solar system. Occupants all found the homes to have good livability characteristics. Problems centered on fine tuning the system, e.g., modifying dampers on a trombe wall, installing shading on a greenhouse.

4. RESEARCH METHODOLOGY AND MODELS IN THERMAL COMFORT RESEARCH

A better understanding of all phenomena investigated by researchers is frequently limited by the availability of appropriate measurement instruments, concepts, and techniques. State-of-the-art advances in the understanding of thermal comfort is no exception. Investigators have developed many novel approaches to collect thermal comfort data in recent years. Several of these methods are particularly intended to be research "tools" for field studies.

Berglund and Gagge explored the use of "operative temperature" measurements (average of air and mean radiant temperature) in their paper. Holmberg and Wyon describe a method for making systematic observations of children in a classroom. Humphreys discusses the technique employed to make photographic records of the behavior of school children. Carroll and Madsen examined thermal discomfort in contrast to the traditional focus of attention on thermal comfort.

- Berglund, L. G. and Gagge, A. P. "Thermal comfort and radiant heat." Proceedings of the Third National Solar Conference, Int'l. Solar Energy Society, Inc., Univ. of Delaware, Newark, Delaware, 1979.

The authors indicate that in passive solar buildings, the air temperature and mean radiant temperatures are seldom equal. Comfort conditions in buildings of this type can be characterized in terms of the operative temperature -- which is approximately the average of the air and mean radiant temperatures (MRT). Humidity levels and air velocities below 30 fpm are said to be relatively unimportant for people engaging in sedentary activities. Finally, slow temperature drifts as occur in passive structures are barely noticed by occupants, providing the operative temperature is in or near the comfort zone.

Another study described in the same report was conducted at the John Pierce Foundation Laboratory to explore the relationship of radiant heat (ERF)* whether "warm" or "cold", on the sensations of thermal comfort or discomfort. The experiment was designed as follows: two infrared quartz lamps were directed downward on a seated subject. At air temperatures, which were varied upward and downward in 1° steps, the subject was asked to adjust the wattage of the IR heater as necessary to produce the appropriate thermal comfort sensation. Simultaneous observations were made of ERF and air temperature for four male subjects who were tested under several different levels of clothed and unclothed conditions. The responses to radiant heat were consistent for each individual subject, but varied greatly from subject to subject.

- Holmberg, I. and Wyon, D. P. "Systematic observation of classroom behavior during moderate heat stress." Educational and Psychological Interactions, No. 37, Malmo, Sweden: School of Education, November 1972.

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* ERF is the additional radiant energy received by the body system from the environment when the temperature of the enclosing wall surfaces or the resulting mean temperature differs from the air temperature. ERF is an energy flux. (Berglund, Gagge)

This investigation explored two different types of measures that can be used in thermal comfort field studies: making systematic observations of a realistic situation, and obtaining performance measurements. Three classes of 9 year old children, and four classes of 11 years olds were exposed for 2 hours at a time to the air temperatures of 20, 27, and 30°C, while performing normal class work in an observation classroom fitted with one-way mirrors. Four unseen observers using identical check lists observed individual children, looking at such things as posture, clothing, concentration, and restlessness. The findings indicated that there were highly significant and linear changes in posture, clothing, and appearance with increasing air temperature. The children tended to adopt a more relaxed and open posture which maximized body surface area. Moderate heat stress caused boys to display decreased concentration, girls, increased restlessness.

During the investigation, standardized language and mathematics tests were administered to the students under all experimental conditions. Significant performance decrements were found as a function of increased temperatures.

- Humphreys, M. A. "Clothing and thermal comfort of secondary school children in summertime." <u>CIB Commission W45 -- Symposium on Thermal Comfort and Moderate Heat Stress</u>, September 1972.

This investigation was a field study of secondary school children. The author collected a photographic record of children engaged in classroom activities under warm weather conditions -- i.e., during the summer. The object of the study was to examine what clothing adjustments were made from standard school uniforms as a result of warm temperature conditions. The standard uniform for boys was grey flannel trousers, a white shirt, school tie, and a V-neck sweater. The girls wore a light cotton dress and a similar pullover. Outer garments could be removed by the students without permission by their teachers. Photographs were taken as a means of determining the relationship between room temperature and clothing adjustments. Information describing room temperature and time of day was included on each photograph.

For children who removed their outer garments, the optimum temperature proved to be 24.3°C. At a temperature of 26.3°C, 17 percent of the children were warm, while 45 percent of them were uncomfortably warm at 28.3°C. Humphreys concluded that the clothing worn by students is a useful indicator of thermal comfort conditions.

- Humphreys, M. A. "Classroom temperature, clothing and thermal comfort a study of secondary school children in summertime." <u>The Building Services Engineer (JIHVE)</u>, 41, (1973).

Classroom temperatures and children's clothing were recorded in several schools during the summer. (Clothing was categorized as in table 6). Every 8 minutes, a specially developed camera system, suspended form the ceiling, took a full field color photograph of the room and of its occupants. The time and room temperature were recorded in each photograph. In conjunction with the photographs, a seven point thermal comfort scale was completed.

It was found that the percentage of children working in shirt sleeves or summer dresses was highly correlated with classroom temperatures. The clothing data were in good agreement with the ratings on the subjective scales.

The author concluded that departures from the prevailing mean indoor temperature should not normally exceed 2°C, that departures from the mean from day to day should not exceed 3°C, nor more than 4° per week.

Table 6. Allocation to Clothing Categories (Humphreys)

Light clothing (R_s)	Heavy clothing (R_j)
Boys: Shirt or T-shirt with long trousers	Boys: Light clothing plus long-sleeved pullover or blazer
Girls: Summer dress Pinafore dress and blouse Skirt and blouse	Girls: Light clothing plus blazer or long-sleeved jumper/cardigan Pinafore dress over long-sleeved jumper/cardigan

Uncommon modes were assigned to whichever category was more appropriate.

- Carroll, J. "An index to quantify thermal comfort in residential building." ASHRAE Transactions, 5, 87(1), (1981).

The discomfort index presented quantifies the thermal discomfort associated with the design and operation of residential buildings during the heating season. Discomfort under steady-state conditions is estimated from the squared difference between the actual temperature and a preferred temperature (which is assumed to vary with clothing and activity levels). A penalty is also assessed for transient discomfort effects. The index allows calibration for individual preferences. The proposed index is similar to the currently used "Predicted Percentage of Dissatisfied," but is said to be simpler and better suited to simulations of residential environments. Simulations can integrate the index over a heating season along with energy use to estimate the overal thermal performance of a building. These two complementary aspects of performance can be combined into an overall index, by using thermostat settings as an indicator of the relative weights that people assign to comfort and energy use.

- Madsen, Thomas L. "Definition and measurement of local discomfort parameters." ASHRAE Transactions, 86, Part 1, (1980).

The author describes the conditions which lead to complaints of thermal discomfort. One set of parameters are concerned with "local" discomfort, which is attributable to draft -- defined as an unwanted local cooling of the body caused by air movement. "Draft" in turn, has been experimentally determined to depend on: (1) mean air velocity, (2) maximum air velocity, (3) frequencies of velocity fluctuations, and (4) the difference between the local air flow temperature corresponding to general thermal comfort.

In this paper, Madsen characterizes the design of a new measuring instrument devised to determine the expected level of local thermal discomfort. The instrument measures the equivalent temperatures on the two sides of a plane element and the equivalent air velocity (convective heat loss from the skin). Mean radiant temperature (MRT), air temperature, and other traditional thermal comfort parameters can also be obtained with the device.

4.1 COMPLEX PERFORMANCE UNDER ADVERSE CONDITIONS

A sizable literature has been developed in response to the needs of the military, the Federal Aviation Administration and National Aeronautics and Space Administration, to better understand the capabiliti perform required tasks under extreme environmental conditions. Most of the tasks examined in this research literature are quite complex manual and mental ones, not typical of most of the activities normally encountered in building environments.

Bensel and Lockhart examined manual task performance during cold conditions. Iampietro, et al., examined performance on a flight simulator, for moderate and high temperature conditions. Mackworth examined both mental and manual abilities in a study of telegraphy. Chiles, et al., Wing and Touchstone, Fine, Cohen and Crist as well as Viteles and Smith, concentrated on the study of mental tasks under conditions of high temperatures. Finally, Wyon and Ryd examined the test performance of school children under a variety of thermal conditions.

- Bensel, C. K. and Lockhart, J. M. "Cold-induced vasodilatation onset and manual performance in the cold." Ergonomics, 17, No. 6, (1974).

This study is an investigation of manual dexterity capabilities during whole-body cold exposure as a function of time to vasodilatation during local cooling. Thirty male subjects were divided into three equal groups on the basis of the time for a 3°F (1.7°C) rise in index finger temperature following immersion of the hand in 4.4°C water; one group took less than 450 seconds, another group took between 450 and 900 seconds, and the third group took longer than 900 seconds. Subsequently, each subject was exposed to ambient temperatures of 15.6°C and -6.7°C, for 3 hours, while performing a battery of six manual tasks, working with bare hands. Manual performance on all tasks was affected adversely at the -6.7°C ambient temperature, and worsened with continued exposure.

The drop in performance on three tasks involving skilled movements of the wrist and fingers was greatest for the "less than 450 second" groups. Within the limits of the present study, the early onset of vasodilatation in local cooling appears to be associated with initially superior performance and subsequently inferior performance on specific manual tasks with increasing durations of whole-body cold exposure.

- Iampietro, P. F., Melton, C. E., Jr., Higgins, E. A., Vaughan, J. A., Hoffman, S. M., Funkhouser, G. E., and Saldivar, J. T. "High temperature and performance in a flight task simulator. (FAA-AM-72-17). Oklahoma City, Okla.: FAA Civil Aeromedical Institute, May 1972.

This experiment was an examination of the effects of high cockpit temperatures on physiological responses and the performance of pilots engaged in a simulated flying task. The object of the study was to determine how accurately the pilots could maintain a pre-determined flight path. Performance was measured in terms of deviations from the ideal flight path. Three cockpit temperatures were used: 25, 43.3, and 60°C, with each flight lasting 50 minutes. Physiological parameters recorded were: Heart rate, deep body temperature, skin temperature, urine output and sweat rate.

The authors found that the performance of complex and critical tasks was more susceptible to degradation under adverse conditions than when simple tasks were performed. Routine flight tasks, e.g., maintaining a level course, were accomplished without serious errors even under the high temperature conditions (43.3 and 60°C).

- Mackworth, N. H. "Effects of heat on wireless telegraphy operators hearing and recording Morse messages." Brit. Journ. Industr. Med., 3, (1946).

This research investigation examined the effects of thermal stress on the performance of telegraphy tasks -- where operators transcribe messages heard over earphones. The subjects were British servicemen who where experienced telegraphers. After a lengthy period of acclimatization (6 to 11 weeks), the experiment was conducted. It required the subjects to perform their tasks for 3 hours per day, 5 days a week. The task was performed under five different environmental conditions, ranging from 85/75°F (29.4/23°C) to 105/95°F (40.6/35°C) (with degree differences among experimental conditions). The air velocity was kept constant at 100 feet per minute. Performance decrements in terms of accuracy were apparent starting with the 95/85°F condition.

- Chiles, W. D. "Effects of elevated temperatures on performance of complex mental task," Ergonomics, 1, (1958).

This experiment investigated the effect of high temperatures on the performance of a complex mental task. The task involved making visual comparisons of a strip of moving cards, with another series of stationary cards. The cards were coded with several different symbols which were quite complex. The task was made more difficult because of the time constraints that were placed upon the subjects. The task was one hour in duration.

The study consisted of two experiments where dry bulb/wet bulb temperatures ranged from 85/75°F (29.4/23.9°C) in series of six conditions. No significant differences in performance were noted among any of the experimental conditions, despite the high levels of temperature that were employed. (The relatively short duration of the task might have contributed to these results.)

- Wing, J. F. and Touchstone, R. M. "The effects of temperature on human performance," Aerospace Medical Research Laboratories AMRL-TDR 65-103, Wright Patterson AFB, Ohio, Sept. 1965.

Fifteen subjects were tested in groups of five. Each group was exposed to temperatures of 72, 90, and 95°F (22.2, 32.2, and 35°C) effective temperature on successive days. The performance study consisted of learning three sets of equated word lists, consisting of six words each. The words were administered aurally to the subjects and their task was to repeat the words on the list without error. Their performance was measured by their accuracy and the number of trials needed to achieve perfect performance.

The authors found that there was a decrement in performance as a function of temperature increases.

- Fine, B. J., Cohen, A., and Crist, B. "The effect of exposure to high humidity at high and moderate ambient temperatures on anagram solution and auditory discrimination." (Technical report EP-138). Natick, Mass. U.S. Army Quartermaster Research and Engineering Center, Environmental Protection Research Division, Oct. 1960.

This research study examined the effects of a variety of temperature and relative humidity conditions on the ability of subjects to perform auditory and mental tasks. Ten subjects were exposed for six periods of one-half hour each on 4 successive days to ambient dry/wet bulb temperatures of 70°/53°F (21.1/11.7°C), 70°/68°F (21.1/20°C), 95°/70°F (35/21.1°C), and 95°/92°F (35/33.3°C), with minimal air movement. The four day sequence was repeated four times during four successive weeks the order of conditions being changed for each replication. The subjects were required to perform two tasks during the study. One task required them to solve anagrams to find the words that could be made from letters which had been scrambled. Twenty-four lists, each containing 42 anagrams, were used in the study. The other task was to match two of three tones presented in a three tone "burst". The nonmatching tone differed from the others with respect to frequency, duration, or intensity. Seventy two groups of three tones constituted the test material.

The authors found that there was no increment or decrement in the performance of either task that could be attributed to either the high humidity or high temperature condition.

- Viteles, M. S. and Smith, K. R. "An experimental investigation of the effect of change in atmospheric conditions and noise on performance." ASHVE, 18, (1946).

In this study, subjects were required to perform seven different tasks, e.g., multiplying a two digit number by a three digit number, during an extended experimental session. They were given training on these tasks during each of four 2 hour sessions which took place on 4 consecutive days. The effective temperatures were systematically varied (73, 80, 87, and 90°F (22.8, 26.7, 30.6, and 32.2°C)) from day to day, with all subjects experiencing all conditions.

The authors found that at the 87°F (30.6°C) ET performance on most of the tasks had significantly deterioriated.

- Ryd, H. and Wyon, D. "Methods of evaluating human stress due to climate. National Swedish Building Research Document, D6, Stockholm, Sweden, 1970.

This study is a followup to earlier experiments performed in specialized laboratories which demonstrated that the test performance of students deteriorated as a result of high room temperatures. The reported investigation was performed under normal conditions in a representative school. Four parallel classes of fifth graders served as subjects. The students were tested in mathematics, reading, and vocabulary skills under three temperature conditions (23, 25, and 27°C) -- other thermal comfort related variables were kept constant. The results indicated that performance was adversely affected by room temperatures that were "only slightly too high" (25 and 27°C). The performance of the children working at the limit of their ability was especially susceptible.

A second experiment was concerned with the ability of children to learn a foreign language under two temperature conditions -- 20 and 27°C. Two classes of 13 year olds were tested on German lessons, which required the children to listen to two lists of words which were new to them. Their task was to learn the "definite article (der, die, das) appropriate for each word. All students participated under each condition. The performance of the task under the 27°C condition was significantly worse than the findings obtained when the temperature was 20°C.

4.2 SENSORY INTERACTIONS

A building consists of a complex environment to those who use it. All of the senses are stimulated simultaneously -- visual, auditory, olfactory, and thermal, for example. Yet, while researchers are aware that in the "real world" a variety of sensory signals is always present, most experimental research dealing with sensory responses employ parametric procedures. That is, one sense modality is singled out for study at a given time, while other environmental conditions are controlled -- i.e., maintained at a constant level. This parametric approach greatly simplifies the task of the researcher, since the problem of possible sensory interactions can be avoided. Unfortunately, we do not live in a parametric world but in an enormously complex one and parametric research is quite artificial from the standpoint of the experimental subject.

Several researchers have investigated interactions among sensory modalities. Houghton investigated the effect of color on feelings of warmth. Fanger et al., examined both color and noise as they influence feelings of thermal comfort. Bursill examined the restriction of peripheral vision during hot and humid conditions. Finally, Rohles studied interactions between thermal and lighting conditions.

- Houghton, F. C., Olson, H. T., and Suciu, "Sensation of warmth as affected by the color of the environment." Heating, Piping and Air Conditioning, Vol. 12, Nov. 1940.

The authors wanted to test the widespread belief that a person's sensation of warmth may be affected by color — e.g., that red colors are "warm" and blue is "cool". A series of tests were conducted in a room with a 6 foot by 6 foot canvas screen, illuminated by a 1000 watt projector, with red or blue filters positioned appropriately. The intention of the study was to equate lighting levels under three conditions, but they could not accomplish this goal because of the characteristics of their instrumentation. The actual measured levels used were as in the table below.

Table 7. Light Intensities Used in "Color" Study of Warmth (Houghton, Olson, and Suciu)

Light Color	Intensity of Incident Light in Plane of Screen Footcandles	Intensity of Light Reflected from Screen Foot-lamberts
White	12.0	9.0
Red	1.2	1.0
Blue	0.6	0.47

The room conditions were kept at 71.5°F (22°C), air movement maintained between 25 and 50 fpm and relative humidity at 50 percent, throughout the study. Subjects looked at the white screen for 1 1/4 hours. A red screen was then illuminated by a red light, which they looked at for 40 minutes, followed by another 40 minute interval of white light, and finally by 40 minutes of blue light on a blue screen. Subjects indicated their feelings of warmth on a five point scale ranging from "cool" to "warm", with "ideal comfort" at the center position. All observations of the two subjects were at the "ideal comfort" position. The study authors concluded that color had no effect on warmth responses under the conditions examined.

- Fanger, P. O., Breum, N. O. and Jerking, E. "Can colour and noise influence man's thermal comfort?" Ergonomics, 20, No. 1, (1977).

Eight women and eight men participated in four thermal comfort studies. In an environmental chamber, each subject was exposed to two types of colored light (extreme red and extreme blue) and to two noise levels (40bBA or 85 dBA), in all four combinations.

In each of the experiment, which were of 2 1/2 hours duration, the preferred ambient temperature was determined for each subject, depending on individual preferences. The subjects were sedentary and wore standard KSU cotton twill uniforms of 0.6 clo. Skin temperatures, rectal temperatures, and evaporative weight loss measurements were taken.

The results of the study indicated that there were light temperature preference differences under the two lighting conditions (lower temperatures under the red), but the differences were so small that they had no practical significance. There were no effects that could be attributed to differences of noise levels.

Finally, no physiological findings were influenced by the color or noise conditions examined.

- Bursill, A. E. "The restriction of peripheral vision during exposure to hot and humid conditions." Quart. Journ. Exp. Psychol., 10, (1958).

This research was intended to discover how successfully subjects can notice and respond to a peripheral signal while performing a continuous central task under conditions of thermal stress. Eighteen heat acclimatized subjects were exposed to temperatures of 70/60°F (21.1/15.6°C) (i.e., dry bulb/wet bulb) and 105/95°F (40.6/35°C), with an air velocity of 120 feet per minute. Subjects were required to respond to peripheral tasks (small signal lights in a semi-circle at angles of 20, 50, and 80° from a fixation point) by depressing an appropriate key, while performing a continuous pursuitmeter task consisting of keeping two pointers aligned by means of a handle control device. Performance measures were obtained from both the tracking and peripheral signal tasks. (Performance decrements occurred as a result of thermal stress; peripheral signals distant from the point of fixation were missed as a function of the degree of heat stress.)

- Rohles, F. H., Bennett, C. A. and Milliken, G. A. "The interaction of the visual and thermal environments on the comfort and acceptance of indoor space. Kansas State Univ. Inst. for Envir. Res., Report 80-04, Manhattan, Kansas, November 1980.

This study examined the effects of several different lighting conditions on thermal comfort in an environmental chamber. The experimental surroundings were also varied. In half of the research trials, the chamber was painted white (as in typical thermal comfort work) or lined with walnut panels. The other research trials were conducted in an "enriched" setting -- simulating a typical open-office setting. Three different fluorescent luminaries were studied: cool-white, warm-white, and daylight. The lighting illuminated the chamber under the painted wall and paneled conditions, as well as when six open-office work stations were simulated. (Three work stations had orange walls and three had blue walls.)

Four hundred and thirty two served under control conditions and a similar number participated under experimental conditions. An equal number of male and female subjects were used in the study. Two temperature conditions were examined: 68°F/50 percent rh (20°C/50 percent rh) and 78°F/50 percent rh (25.6°C/50 percent rh). Each condition was replicated three times. Subjects were run six at a time in the KSU chamber. Skin temperatures were recorded, as were thermal comfort and thermal sensation votes. The results of the study indicated that thermal sensation was not affected by the "starkness" or "richness" of the surroundings. However, different thermal comfort votes were noted among some conditions -- with "rich" and "orange" decor resulting in somewhat greater comfort.

5. SUMMARIES OF THERMAL COMFORT DATA FOR DESIGN

A number of investigators (and organizations) have organized thermal comfort findings to make them more accessible to designers.

McIntyre describes a simplified method of estimating optimum "subjective temperature" as a function of activity level and clothing insulation. Arens et al., prepared a new bioclimatic chart for passive solar design. ASHRAE standard 55-81 describes thermal environmental conditions for human occupancy.

- McIntyre, D. A. "Design requirements for a comfortable environment." Electricity Council Research Centre Report M1185, Capenhurst, Chester CH1 6ES, U.K., Oct. 1978.

This paper provides a simplified method of estimating the optimum "subjective temperature" as a function of activity level and clothing insulation. (The sensation of themal comfort is said to be primarily dependent on the "general feeling of warmth".) Subjective temperature is an index defined in terms of a standard environment, and is calculated readily from enviromental information.

The variation of thermal sensations between different people, and in the same person from time to time, is demonstrated on the basis of research findings. These sources of variability have important consequences for temperature control. The findings of field surveys show that people adapt their behavior to prevailing conditions. No universal comfort temperature is apparent.

Potential sources of thermal discomfort are discussed and whenever possible, working limits are given to describe the conditions where most people will be thermally comfortable. Finally the concept of "comfort" is discussed, with the conclusions that the existing concepts of acceptability need to be refined.

This paper draws from extensive field data and laboratory studies in the formulation of a new approach.

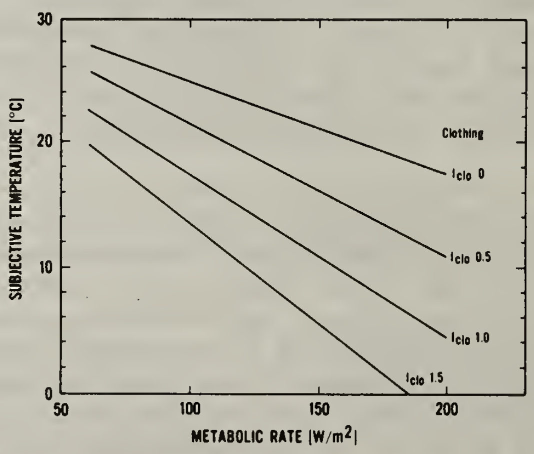

Figure 28. The subjective temperature required for comfort as a function of activity and clothing insulation. (McIntyre)

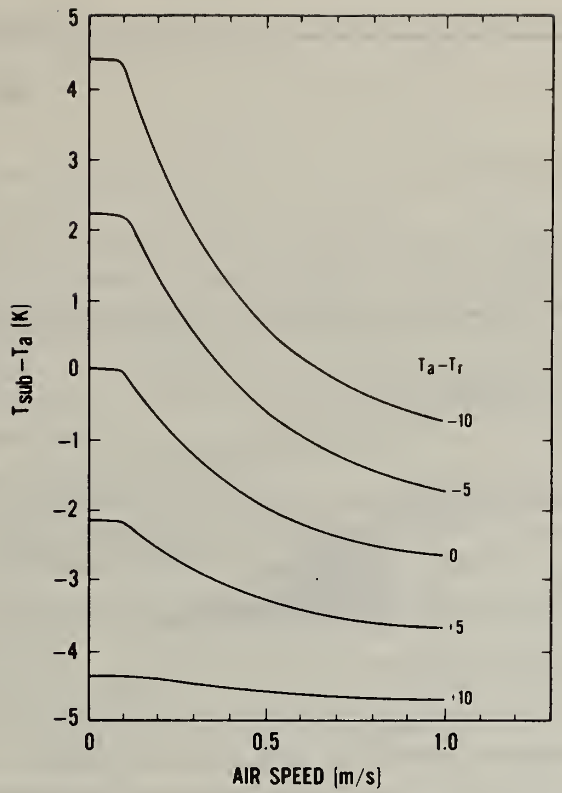

Figure 29. The relation between subjective temperature, T_{sub}, and the physical variables of air temperature T_a, mean radiant temperature, T_r, and air speed v. The differential (T_a - T_r) is determined by the heating system and building structure. (McIntyre)

- Arens, E., Gonzales, R., Berglund, L., McNall, P. E. and Zeren, L. "A new bioclimatic chart for passive solar design." Proceedings of International Congress on Building Energy Management, Lisbon, Portugal, May 1980.

Spaces heated by passive solar systems tend to vary more than mechanically controlled spaces, e.g., high radiant temperature differences resulting from solar heated components such as trombe walls. They also have stronger radiant fields and more air motion than conventionally controlled environments. Designers of passive solar systems must consider how this wider variety of climatic conditions affect thermal comfort in formulating their design programs. The authors of this report modified an earlier bioclimatic chart widely used by architects and engineers to account for recent research findings, especially as they might impact passive solar buildings.

The criteria for the boundaries of the comfort zone are based upon ASHRAE standard 55-81. Figure 30 presents the bioclimatic chart in a psychrometric format.

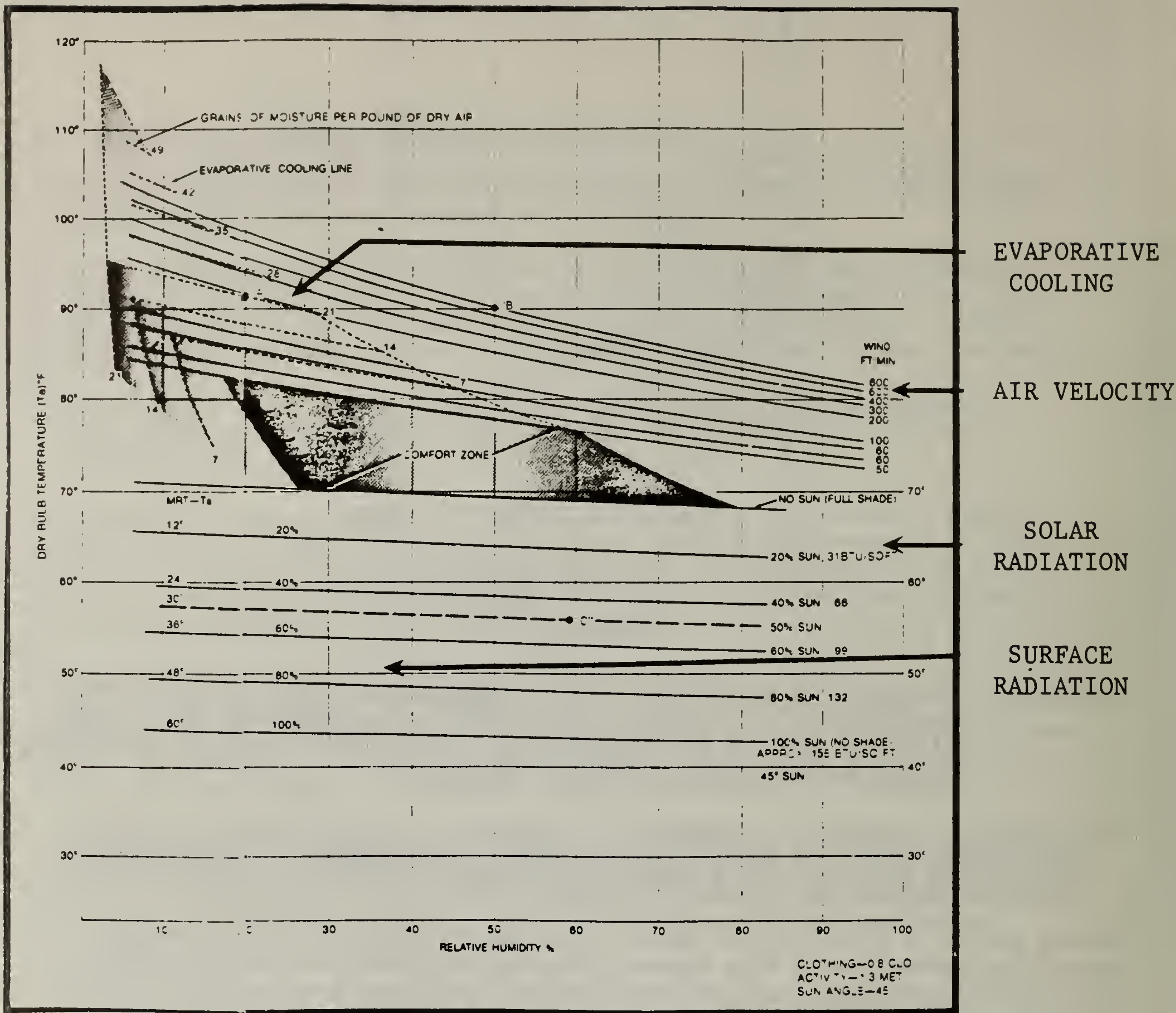

Figure 30. Bioclimatic chart, psychrometric format. (Arens, et al.)

- ASHRAE, "Standard 55-81, Thermal Environmental Conditions for Human Occupancy", American Society of Heating, Refrigerating and Air-Conditioning Engineers, Atlanta, 1981.

The standard specifies the combination of factors necessary for thermal comfort in the built environment. The important environmental parameters are temperature, radiation, humidity, and air movement, while the important personal parameters are clothing and activity.

In both the present and past ASHRAE comfort standards, the basic aim is to specify conditions that are thermally acceptable to 80 percent or more of the occupants. The standard includes adjustments that can be made for clothing, activity, air movement and temperature drifts that give greater flexibility and often have energy saving potential. In addition, the standard introduces limits on the thermal nonuniformities in the space to decrease the probability of local discomfort.

6. BUILDING DESIGN

Physical factors such as orientation, mass, shape, glass, and location, to name a few, affect the success of a building in terms of energy conservation, natural ventilation and occupant acceptance of the thermal environment. The design must put the physical elements together in such a way as to take advantage of the local climate. Being able to predict the environment in a passive building is also important. These and other aspects of building design are discussed in the following.

Loftness describes the impact of climatic factors on thermal comfort. van Straaten describes the relationships between outdoor temperature conditions and design characteristics which influence thermal comfort. Arnold indicates the effectiveness of natural ventilation as a substitute for air conditioning of spaces. Gupta discusses features of building design as they affect the thermal performance of a building. He describes a computer procedure that he developed to assess these effects. Milbank describes a method of incorporating thermal comfort findings into design, at an early stage of the design process. Finally, Hayter proposes a procedure for evaluating thermal comfort in passive solar buildings, based upon operative temperatures.

- Loftness, V. "Identifying climate design regions and assessing climatic impact on residential building design. (Technical paper No. 1). Washington, D.C.: AIA Research Corporation, Winter 1977.

The research described in this paper identifies and assesses the impact of climatic factors on human thermal comfort and the design of energy conserving buildings. The analysis of base (temperature and humidity) climatic data from 130 United States cities was undertaken in relation to a comfort zone based upon accepted temperature and humidity ranges. The conditions were predominantly: "heating", "cooling", and "comfortable". The potential influence of other climatic conditions were examined (e.g. radiation, wind) as they are likely to affect the comfort zone. That is, an expanded comfort zone was defined, and then used to describe residential energy conserving design solutions in response to all climatic conditions, by identifying regionally available climatic forces for making increased use of natural comfort conditions.

- van Straaten, J. F. "Environmental control by building procedure. The South African Builder, 50, (3,4,5), (1972).

The author describes how building design principles can be used to optimize environmental control with respect to several climatic conditions, i.e., air temperatures, solar radiation, wind, and moisture. He covers design issues such as lightweight and heavyweight construction, color, glazing materials, and natural ventilation. The author does not deal with environmental engineering methods of achieving acceptable thermal performance.

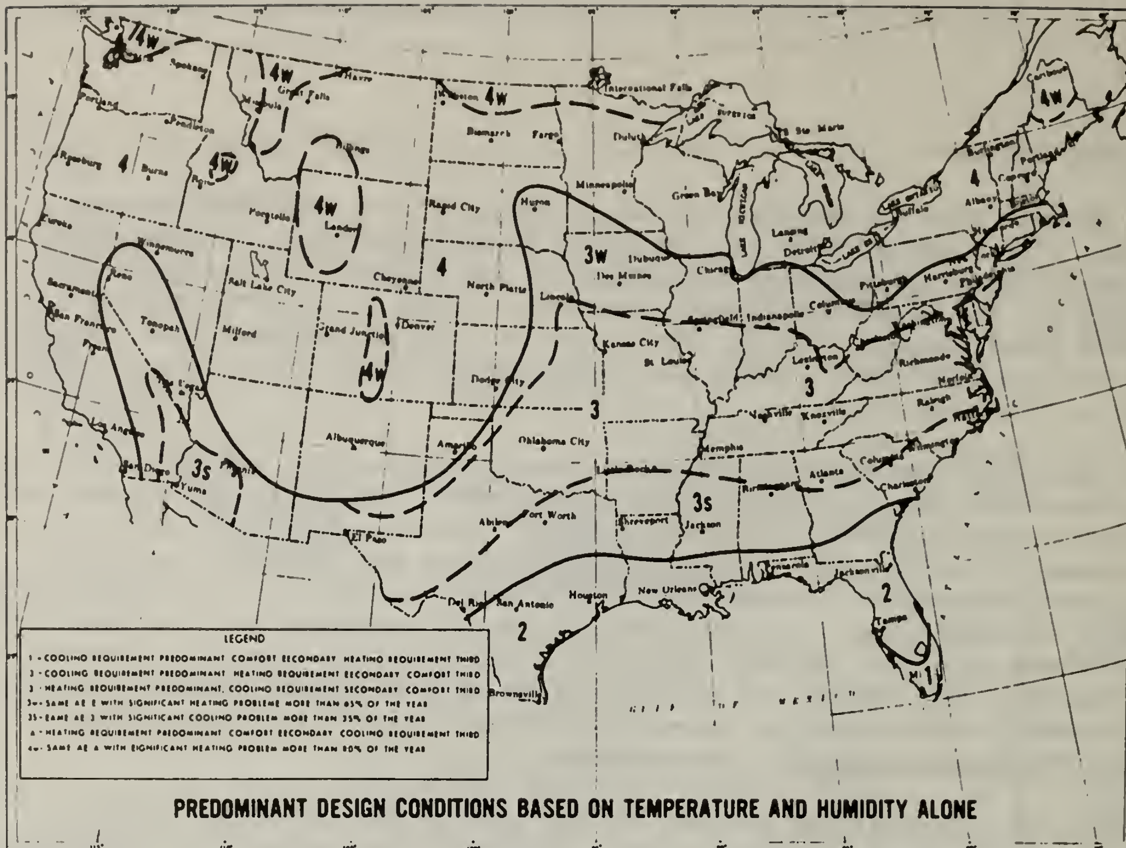

Figure 31. Predominant design conditions based on temperature and humidity alone. (van Straaten)

- van Straaten, J. F. and van Deventer, E. N. "The functional aspects of building design in warm climates with particular reference to thermal and ventilation considerations. International Journal of Biometeorology, 8 (2), 155-163 (1964).

The functional design of buildings is discussed with particular reference to thermal and ventilation considerations. Indoor environmental conditions in buildings which are and are not air conditioned, are dealt with briefly. The lack of useful information concerning the effects of directional radiation in warm climates is emphasized. A method is outlined, which can be used for a rational assessment of outdoor environmental conditions in terms of the probability of the joint occurrence of various combinations of meterorological conditions, e.g., cloud cover, wind, etc.

The influence of structural design (e.g., light weight vs heavy weight) on the thermal performance of buildings is discussed with respect to the relationship of indoor and outdoor temperatures. The need for ceiling insulation is specifically stressed.

- Arnold, D. "Comfort air conditioning and the need for refrigeration." ASHRAE Transactions, 84, Part 2, (1978).

The author questions the present use of refrigeration to provide acceptable environmental conditions. He describes a procedure of using a variable flow rate ventilation system to maintain thermal comfort, that takes advantage of the "free cooling" available at night. A simulation model was developed, based on a model of a controlled ventilation system, which calculates the variation in internal temperature using weather data, solar radiation, and air temperature from weather tapes.

The degree of thermal comfort achieved using this technique was evaluated on the basis of field studies of thermal comfort. The results indicated that thermal comfort conditions would be achieved 95 percent of the time. Arnold suggests that the technique of simulating building thermal behavior, calculating the band width of temperatures covering 95 percent of occupancy time, and examining the level of comfort achieved, could be extended to a wide range of buildings and climates -- thereby providing a means of predicting whether refrigeration is needed to provide thermal comfort for buildings in warm climates.

- Gupta, C. L. and Spencer, J. W. "Building design for optimal thermal performance." Australian Refrigeration, Air Conditioning and Heating, 24 (11), (1970).

This paper examines the interactive aspects of building design and air-conditioning loads as affected by as many as 15 variables specifying such factors as insulation, inertia, glazing, shading, siting, and surface treatments. A description is given of a computer-based procedure for evolving building performance specifications and which allows for minimum departure from comfort conditions, or for minimum operating loads on air-conditioning plant. Results are discussed for the application of this method to the thermal design of panelized residential construction for use in typically hot dry, hot humid, coastal, and temperate climates.

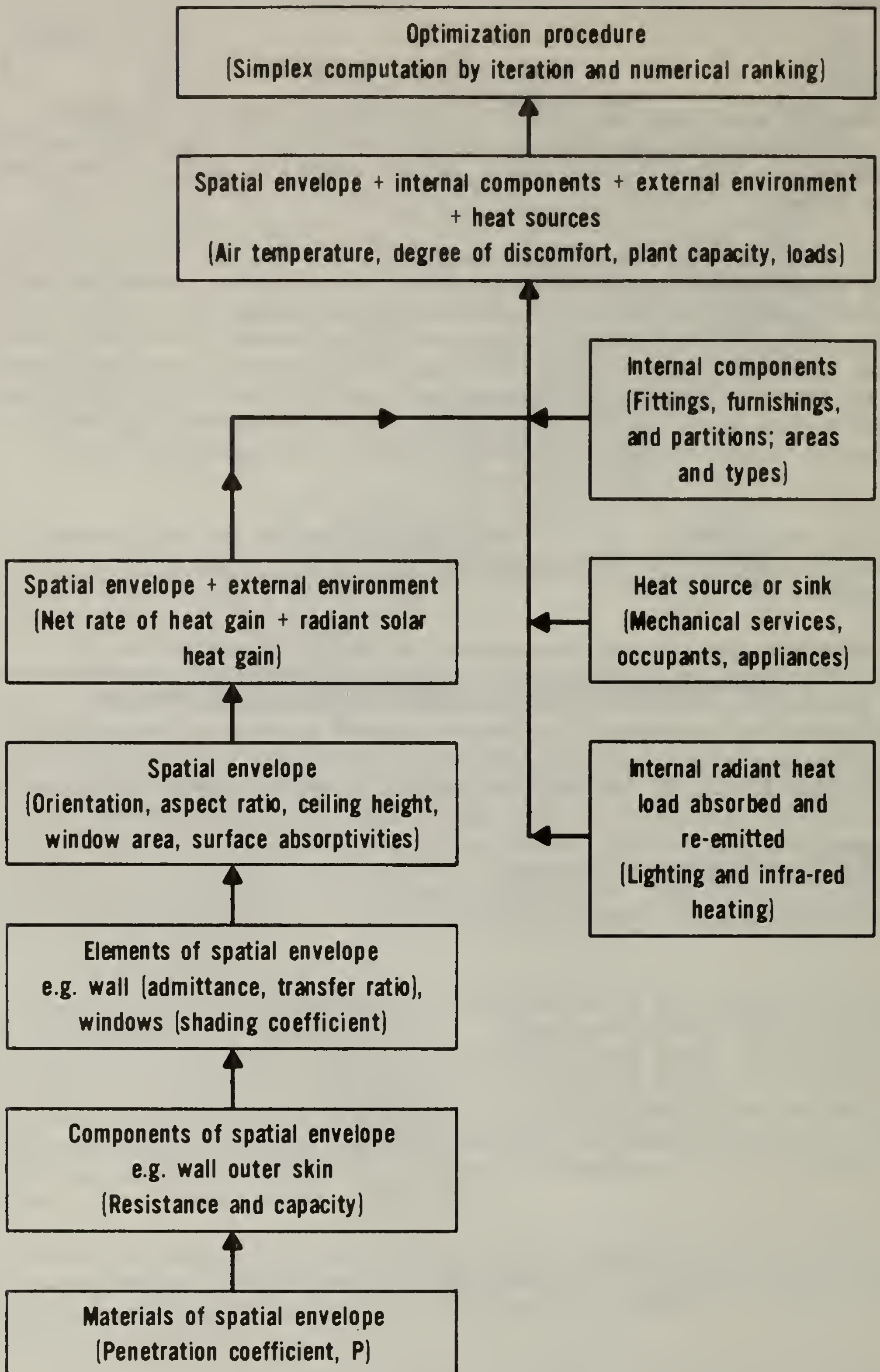

Figure 32. Hierarchy for optimizing thermal performance of residential buildings. (Gupta and Spencer)

• Milbank, N. O. "A new approach to predicting the thermal environment in buildings at the early design stage." Building Research Establishment Current Paper 2/74, January 1974.

The paper indicates that existing computer programs for thermal predictions do not produce suitable information for architects, particularly at the early stages of design. It suggests that architects and engineers require rather different information about thermal performance at different stages of design work -- i.e., at the earliest design stage the architect needs qualitative data which broadly indicates the extent of services needed for a particular design -- and in particular whether natural or mechanical ventilation, and even cooling, is necessary.

The author shows that it is not realistic to consider thermal conditions in isolation: e.g., the feasibility of achieving the natural desired ventilation rate and the use of artificial lighting are also important. Sample design aids are included in the report. For example, figure 33 shows the theoretical effect of varying the period and quantity of fresh air in a naturally ventilated office -- an attempt to simulate different ways of using windows.

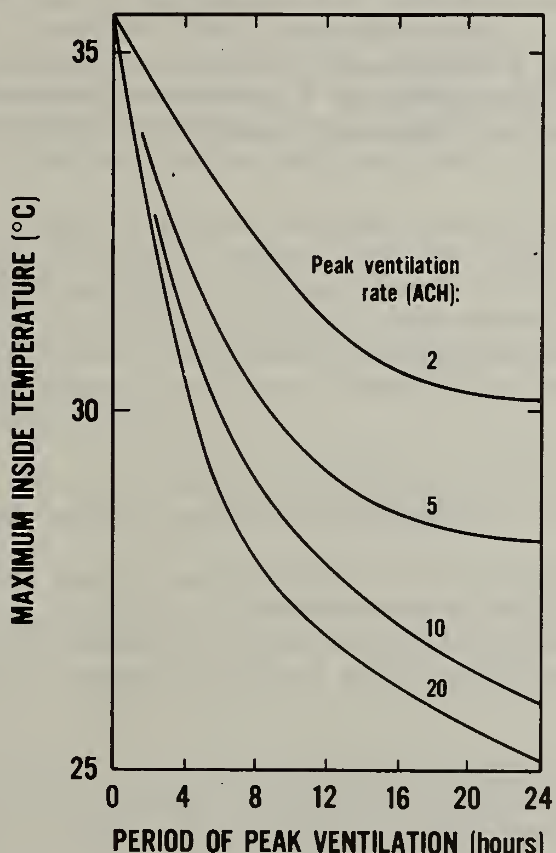

Figure 33. Calculated indoor temperatures are sensitive both to the rate of fresh air supply and the period of ventilation (background ventilation rate: 0.5 ACH, room with 80 percent glass with internal blind). (Milbank)

- Hodgson, T. and Lotz, F. J. "Control of thermal environment in buildings." South African Mechanical Engineer, 14, (10), 1-8 (1965).

This paper describes various factors which affect the heat gains and losses through building structures and which therefore have a direct effect on the environmental conditions within a building structure, particularly with respect to air temperature and the directional intensities from surrounding surfaces.

The effects of thermal insulation, solar heat gains through glass, ventilation, absorbtivities of external surfaces to solar radiation, heat storage, and orientation of a building, on indoor climate are discussed. The author indicates how building design procedures can be used to influence the quality of the thermal environment of buildings, with and without the use of evaporative cooling.

- Hayter, R. B. "Defining thermal acceptability in structures passively heated by solar energy," ASHRAE Transactions, 88 (1), (1982).

The paper advocates the accumulation of the deviations of operative temperature from the comfort conditions of ASHRAE Standard 55-81 and their duration.. The sum of the deviation duration product over a season or day could be used to rate or compare the comfort performance of a passive solar residence much like degree days are used to judge the seasonal, thermal severity of a climate.

7. INSTITUTIONAL FACTORS AFFECTING ACCEPTANCE OF PASSIVE SOLAR DESIGN

The widespread acceptance of technological change is not determined solely by the merits of engineering advances. Policy makers and consumers importantly influence such changes.

Shama and Jacobs examined the role of the advocate and the policy maker as they influence solar energy policy. Burns examined behavioral and social models which might contribute to an understanding of energy decision making and behaviors.

- Shama, A. and Jacobs, K. "Social values and the solar energy policy: The policy maker and the advocate. (SERI/RR-51-329). Golden, Colorado: Solar Energy Research Institute, October 1979.

This investigation examines two key groups who are of primary importance in determining energy policy: (1) those responsible for designing, implementing and evaluating solar energy policies, and (2) those outside government who play an active role in understanding or promoting a more rapid adoption of solar energy.

The study was performed by reviewing the pertinent literature dealing with the topic and using a content analysis to classify and cluster the values that each group associates with solar energy. Based on these findings, the value clusters of each group was ranked and compared.

The authors found that the different orientations of the groups seem to be attributable to the particular values that they have, and to the different weights (importance) assigned to these values. For example, the policy makers attached much greater weight to economic considerations than the advocates -- 52 percent to 33 percent. This latter figure was matched for social values in the case of the advocates, which was considerably higher than the weight assigned by the policy makers.

- Burns, B. A. "The relevance of behavioral and social models to the study of consumer energy decision making and behaviors." SERI/RR-722-341, Nov. 1981.

This report reviews social and behavioral science models and techniques for their potential applicability in understanding and predicting consumer energy decision making and behavior. Three major issues were examined: models of adaptation to social change, decision making and choice behavior and the diffusion of innovation.

Five primary components of the models were identified and compared: (1) situational characteristics, (2) product characteristics, (3) individual characteristics, (4) social influences, and (5) the interaction of components or decision rules.

8. REFERENCE BOOKS

A review of publications dealing with thermal comfort in passive solar buildings would be incomplete without mentioning major reference books on the topic. Following is a listing of three excellent and current reference works. The chapter headings are listed to suggests the scope of each work.

Fanger, P. O. Thermal Comfort -- Analysis and Applications in Environmental Engineering, McGraw Hill, N.Y., 1972.

Chapter 1 Introduction

Chapter 2 Conditions for Thermal Comfort

Chapter 3 The Influence of Certain Special Factors on the Application of the Comfort Equation

Chapter 4 Practical Assessment of Thermal Environments

Chapter 5 Calculation of Mean Radiant Temperature

Chapter 6 Radiation Data for the Human Body

Chapter 7 Thermal Environmental Analysis

McIntyre, D. A. Indoor Climate, Applied Science Publishers Ltd., London, England, 1980.

Chapter 1 Introduction

Chapter 2 Physics of Heat Loss

Chapter 3 Measurement and Instrumentation

Chapter 4 Physiology of Thermoregulation

Chapter 5 Thermal Sensation

Chapter 6 Comfort Indices

Chapter 7 Field Surveys

Chapter 8 Practical Aspects of Discomfort

Chapter 9 Ventilation and Air Quality

Chapter 10 Heat Stress and Cold Stress

Chapter 11 Temperature and Performance

Chapter 12 Design Requirements for a Comfortable Environment

Cena, K. and Clark, J. A., Editors, Bioengineering, Thermal Physiology and Comfort, Elsevier Scientific Publishing Co., Amsterdam, Holland, 1981.

Part I. Physical Principles and Measurements

Chapter 1 The physics of the microclimate

Chapter 2 Measurement of thermal balance of man

Chapter 3 Evaluating the effects of clothing on the wearer

Chapter 4 Human skin temperature and convective heat loss

Part II. Models and Indices of Heat Exchange

Chapter 5 Rational temperature indices of thermal comfort

Chapter 6 Required sweat rate as an index of thermal strain in industry

Chapter 7 Modelling of heat transfer in man

Part III. Physiology, Work and Exercise

Chapter 8 Exercise physiology and sensory responses

Chapter 9 Thermal physiology of man in the aquatic environment

Chapter 10 Climatic change and acclimatization

Chapter 11 Man in extreme environments, problems of the newborn and the elderly

Chapter 12 Physiological signals for thermal comfort

Part IV. Comfort, Its Specification and Consequences

Chapter 13 Design requirements for a comfortable environment

Chapter 14 Prediction of local discomfort for man

Chapter 15 The dependence of comfortable temperatures upon indoor and outdoor climates

Chapter 16 The effects of moderate heat stress on mental performance

9. RESEARCH NEEDS

Areas where research would be helpful for the development and acceptance of passive solar systems are identified in the following section. Some of the important areas for study are: thermal nonuniformities and their effect on the occupants; productivity or performance decrements from continuous long term exposure to environments that deviate from conditions ideal for comfort-simulating conditions where people live or work in such environments (i.e., studies lasting several weeks or months, and field validation of laboratory results; the degree of control of room temperature to assure thermal comfort.

- Humphreys, M. A. "Desirable temperatures in dwellings. Building Services Engineer, 44, (8), (1976).

The author discusses the relation between energy expenditure, clothing, and room temperature. Temperatures which would be comfortable for sleeping, sitting and afor various standing activities are given in terms of clothing worn, e.g., light, medium. The probable levels of activity in various rooms in a dwelling are considered and suggestions are made for desirable temperatures for winter and summer. Subject areas requiring research are mentioned; they include: summer and winter bedroom temperatures, comfortable temperatures for children, and the degree of control of room temperature to assure thermal comfort.

Fanger, P. O. "Future research needs concerning the human response to indoor environments" ASHRAE Transactions, 84, Part 1, (1978).

Fanger discusses future research requirements under a variety of subject area headings:

Thermal Neutrality -- Studies of transient conditions are needed. Step changes, gradual changes, and temperature swings all influence feelings of thermal comfort and thermal discomfort in ways that are not sufficiently understood.

Local Thermal Discomfort -- Only a limited number of studies have dealt with this subject, and they have revealed that people differ greatly from one another with respect to local thermal discomfort.

Asymmetric Radiation -- Studies are needed to establish limits for asymmetric radiation for vertical and horizontal surfaces.

Children -- Most thermal comfort data are based upon studies of college students. In recent years, the elderly have received some research attention. However little is known about the thermal comfort requirements of children of different age groups.

Draft -- This is one of the most common complaints in buildings. Measurement methods are needed to quantify velocity of air movement as well as velocity fluctuations in ventilated spaces.

Vertical Temperature Gradients -- Studies are needed to establish guidelines for acceptable vertical temperature gradients. Both positive and negative gradients require investigation.

Spot Heating and Cooling -- A potentially great saving of energy is possible if local heating of the hands and feet during the winter can be substituted for heating an entire building. Fanger recommends that feasibility studies be conducted of this alternative method of providing thermal comfort for building occupants.

Performance and Productivity -- While this relationship has received some research attention in the past, few definitive findings are available. Extended laboratory studies are recommended where people perform tasks which realistically simulate various work situations. The studies should be of several weeks duration, 8 hours per day.

- Goldman, R. F., Berglund, L. and Rohles, F. H. Jr. "Human Factors in Dynamic Control of Environmental Conditions." Workshop on Dynamic Response of Environmental Control Processes in Buildings. Ed. Tree, D. Purdue Univ., Lafayette, Indiana, March 1979.

This paper summarizes a number of key areas of thermal comfort research and identifies research requirements for energy conservation purposes. Among the research needs noted are the following:

Steady-State Environments

- Validation of steady-state models at the boundaries and outside of the thermal comfort recommendations specified in 55-81.

- Effects of acclimatization on the upper and lower boundaries of comfort temperatures.

- Effects of short occupancy or sudden transients across the comfort zone.

- Altered clothing (improved insulation) as a means of extending comfort to cooler temperatures.

Studies of Design Conditions for Dynamically Altering Environments

- Applicability of steady-state models to slow drift ramps.

- Validation of dynamic response comfort prediction model.

- Applicability of the dynamic cycles model to ramp conditions.

9.1 RESEARCH NEEDS--SUMMARY

Steady-State vs Variable Conditions

Until quite recently the assumption has been made by both researchers and engineers that thermal comfort is dependent upon steady-state conditions, and that transient changes are undesirable, and therefore to be avoided. Some researchers are now questioning this assumption, and hypothesizing that unchanging conditions may result in monotony, and that variations in thermal environmental conditions may be desirable.* Furthermore, significant energy savings are possible when building design criteria permit temperature changes. Research is needed to better understand the tradeoffs associated with steady-state and variable thermal environments. Investigations should simulate the environments experienced when people move from outdoors to indoors, and when they move from place to place within a buildings, when the spaces are "thermally" different from one another. Step changes and slow temperature drifts both require investigation, as well as rapid sinusoidal swings -- which some people claim has beneficial effects on building occupants.*

Individual Differences and Thermal Comfort

The vast majority of thermal comfort research has been based upon studies of college students and young military personnel. While the aged population has received some research attention in recent years, the thermal comfort requirements of this age group is not sufficiently understood. The lack of adequate data is even more apparent when we turn our attention to the needs of children, who have seldom been studied in laboratory settings. Other subgroups of the population which merit attention are the handicapped and cultural groups within the United States. Finally, studies are necessary to compare thermal comfort findings obtained in the United States with the considerable body of data acquired in other countries -- using identical (or comparable) research procedures.

Local Thermal Discomfort on the Body

Fanger describes the situation where, although a person is in a thermally neutral condition, if one part of the body is warm and another part is cool then considerable discomfort may result. This effect can be the result of an asymmetric radiant field, local convective cooling of the body by a draft, contact with a warm or cool floor, by a vertical air temperature gradient, or even due to a nonuniformity of clothing. Studies of local discomfort are necessary to determine the effects of these conditions on thermal acceptability. A complicating factor in developing an adequate research program to deal with the problem is that findings to date indicate that individuals differ considerably from one another with respect to tolerating local body discomfort.

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* Discussions in ASHRAE Committee TC2.1, "Physiology and the Human Environment."

Asymmetric Radiation

An important feature of many passive solar designs is the lack of uniformity of thermal conditions, since the storage of solar energy is often accomplished as an integral part of the building structure. While radiant asymmetry has been the subject of several investigations in the past several years, its effects on thermal comfort are still not sufficiently understood. Of particular importance is the need to study passive solar buildings under field conditions -- examining both vertical and horizontal sources of radiant heating and cooling, and to determine their effects upon thermal comfort.

Clothing

The thermal interaction of man and clothing is not sufficiently understood -- especially under non steady-state conditions. Clothing which is not uniformly distributed over body surfaces can result in non-uniformities in skin temperature and blood flow, resulting in thermal discomfort. These effects are likely to increase as a function of the extent that an environment deviates from uniform and thermally neutral conditions.

Spot Heating and Cooling

As a means of conserving energy in buildings, one approach is to provide localized heating and/or cooling on the occupants of spaces, rather than to condition the entire environment, as in current practice. This approach might be a useful one in large enclosures with widely separated work spaces (assuming that temperature control is required only for the building occupants.) Studies are required to determine the feasibility and acceptability of this approach. The use of spot heating and cooling should also be investigated in the context of providing auxiliary conditioning of spaces.

Field Validation of Laboratory Findings

To date, most thermal comfort research has been performed under laboratory conditions. Ultimately, however, the test of laboratory based findings is their applicability under real-world conditions. Such validation studies performed in the "field" are very difficult to conduct because of the multiplicity of variables and their complex interactions -- e.g., lighting, acoustics; social and psychological. For example, in the case of passive solar designs, dependence on sunlight often leads to designs which maximize glazed areas -- which in turn often lead to problems of "glare".

A major research requirement is the development of appropriate field measurement techniques to validate laboratory findings, and to account for the complexity of the "real world" environment.

Performance and Productivity

While many studies have been conducted to better understand the relationship between the thermal enviroment and performance (productivity) our understanding of this problem area is still quite limited. Those studies which have demonstrated straightforward cause-effect relationships have typically been performed under extreme conditions (hot or cold) and have employed very demanding tasks to measure performance. Neither the environmental conditions nor the tasks have been representative of the situations encountered by most people in buildings.

Studies are required where subjects are engaged in meaningful tasks for extended periods of time -- 8 hours per day for weeks or even months. In studies of performance and productivity it is essential to consider the complexity of the "real world" environment — in order to better understand the contribution of thermal comfort and/or thermal discomfort to performance and productivity.

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NBS-114A (REV. 2-8C)

U.S. DEPT. OF COMM. BIBLIOGRAPHIC DATA SHEET (See instructions)	1. PUBLICATION OR REPORT NO. NBSIR 82-2585	2. Performing Organ. Report No.	3. Publication Date October 1982

4. TITLE AND SUBTITLE

Thermal Comfort in Passive Solar Buildings -- An Annotated Bibliography

5. AUTHOR(S)

Dr. Arthur I. Rubin

6. PERFORMING ORGANIZATION (If joint or other than NBS, see instructions)

NATIONAL BUREAU OF STANDARDS
DEPARTMENT OF COMMERCE
WASHINGTON, D.C. 20234

7. Contract/Grant No.

DE-AI01-76PR06010

8. Type of Report & Period Covered

9. SPONSORING ORGANIZATION NAME AND COMPLETE ADDRESS (Street, City, State, ZIP)

U.S. Department of Energy
Office of Solar Heat Technologies
Passive and Hybrid Solar Energy Division
Washington, D.C. 20585

10. SUPPLEMENTARY NOTES

☐ Document describes a computer program; SF-185, FIPS Software Summary, is attached.

11. ABSTRACT (A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here)

This study consists of a selective annotated bibliography of thermal comfort research organized around major subject areas, and recommendations for future research concerned with thermal comfort in passive solar buildings. No attempt has been made to provide a comprehensive treatment of this extensive area of investigation--as this would be beyond the scope of the project under which this work was performed. Instead, the intent has been to sample the range of experimental variables and research methods employed by thermal comfort researchers--and to indicate significant findings.

The major goals for the present report are to describe the state-of-the-art of thermal comfort research and findings and to indicate the research needed to develop the information required by those responsible for specifying, designing and operating passive solar buildings.

12. KEY WORDS (Six to twelve entries; alphabetical order; capitalize only proper names; and separate key words by semicolons)

ASHRAE comfort standards; asymmetric heating/comfort; behavioral studies; clothing/thermal comfort; comfort envelope; human factors; passive solar/thermal comfort; performance/thermal comfort; temperature drifts/comfort; thermal comfort.

13. AVAILABILITY

[XX] Unlimited
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☐ Order From Superintendent of Documents, U.S. Government Printing Office, Washington, D.C. 20402.
[XX] Order From National Technical Information Service (NTIS), Springfield, VA. 22161

14. NO. OF PRINTED PAGES

81

15. Price

$10.50

USCOMM-DC 6043-P80