A STUDY OF THE THERMAL ENVIRONMENT IN APARTMENTS OF THE ELDERLY

by

ROGER PHILLIP VOLMER

B. S. M. E., Kansas State University, 1973

A MASTER'S THESIS

submitted in partial fulfillment of the

requirements for the degree

MASTER OF SCIENCE

Department of Mechanical Engineering

KANSAS STATE UNIVERSITY

Manhattan, Kansas

1975

Approved by:

Ralph O. Turnquist

Major Professor

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF SYMBOLS

t_{db}	Dry Bulb Temperature, °F
t_g	Globe Temperature, °F
VEL	Local Airspeed, FPM
t_{mrt}	Mean Radiant Temperature, °F
$t_{adj\ db}$	Adjusted Dry Bulb Temperature, °F
RH	Relative Humidity, %
P_s	Saturated Water Vapor Pressure, mm Hg
P_a	Partial Vapor Pressure of Water, mm Hg
I_{cl}	Clothing Insulation Value, clo

CHAPTER ONE

INTRODUCTION

BACKGROUND

Thermal comfort is defined in the American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE) Standard 55-74 [1]* as "that condition of mind which expresses satisfaction with the thermal environment". In other words, one is not consciously aware of any desire to change the thermal conditions of his/her surroundings. While temperature and humidity are certainly important factors influencing one's expression of comfort, Rohles [2] lists as many as eighteen environmental variables which may affect how one "sizes up" his/her surroundings. He has organized these variables under three categories. First of all, there are the physical factors including such variables as sound, temperature, humidity, force field or radiation. Those factors having to do with the persons themselves, the organismic factors, include age, sex, diet, et cetera. The third category includes the reciprocative factors or those variables such as clothing or activity which interact between the subject and his/her surroundings. Rohles [2] has defined environmental psychology as "the study of behavior as it is affected by one or more factors in the physical environment". The engineer concerned with designing a comfortable interior environment needs to be an "environmental psychologist". It is from his knowledge of physical, physiological, and psychological explanations of thermal comfort, as well as direct experimental findings, that he can develop standards and design criteria to be used in practice.

*Numbers in brackets refer to references listed on page 38 .

LITERATURE SURVEY

The first major attempt at determining a "comfortable" combination of environmental parameters was the work done by Houghten and Yaglou in 1923 [3]. The result of their study was an index called effective temperature (ET), which correlated the effect of dry bulb temperature, relative humidity and airspeed on the thermal sensations experienced by the human body.

Other significant work, through 1966, is summarized in Table 1, reproduced from Rohles and Nevins [4,5].

More recent contributions include the formulation of a comfort equation developed by Fanger [6]. This equation expresses the functional relationships among air temperature, humidity (partial vapor pressure), mean radiant temperature, relative airspeed, activity level (internal heat production) and clothing insulation such that, at steady state, thermal comfort conditions might exist for the highest possible percentage of college age Americans. Fanger's book Thermal Comfort [7], published in 1970, contains the development of empirical equations to calculate the Predicted Mean Vote (PMV), an indication of thermal sensation. This is an index which may be determined from a comprehensive set of tables once the environmental variables have been determined. Perhaps more important is the fact that by knowing the PMV one can determine the Predicted Percentage of Dissatisfied (PPD) among a group of people.

An alternative to interpreting thermal comfort data as vote lines or thermal sensation lines on a psychrometric chart was a comfort zone or envelope prescribed by Rohles and Nevins [8]. Rohles [4,9,10] later proposed a set of fifteen conditions which he identified as the Modal Comfort

Table 1. Chronological Listing of the Major Research Studies in Thermal Comfort Reprinted from Rohles and Nevins [4], adapted from Nevins [5].

Date	Environmental Specifications	Dry Bulb Temperature For RH=40%	References
1914	68 F DBT 40% RH	68	Report of the New York State Commission on Ventilation, E. P. Dutton & Co., New York 1923.
1923	66-72 F DBT 19-61% RH	66-72	Katz, A. P., Humidity Requirements for Residences, Transactions of the American Society of Heating and Ventilating Engineers, Vol. 29, 1923.
1923	62-69 ET 64 ET (optimum)	68	Houghten, F. C. and Yaglou, C. P.. "Determining Lines of Equal Comfort," and "Determination of the Comfort Zone," Transactions of the American Society of Heating and Ventilating Engineers, Vol. 29, 1923.
1925	63-71 ET 66 ET (optimum)	71	Yaglou, C. P. and Miller, W. E., Effective Temperature with Clothing, Transactions of the American Society of Heating and Ventilating Engineers, Vol. 31, 1925.
1929	66-75 ET 71 ET (optimum)	77	Yaglou, C. P. and Drinker, P., The Summer Comfort Zone, Transactions of the American Society of Heating and Ventilating Engineers, Vol. 35, 1929.
1939	64.8-76 OF ET 71.8 F ET (optimum)	78	DuBois, E. F., Heat Loss from Body, Bulletin, N. Y. Academy of Medicine, 2nd Series, Vol. 15, 1939.
1941	68 ET (optimum)	74	Houghten, F. C., Gunst, S. B., and Suciu, J., Radiation as a Factor in Sensation of Warmth, Transactions of the American Society of Heating and Ventilating Engineers, Vol. 47, 1941.
1938-1956	73-77 DBT 25-60% RH	73-77	Fahnestock, M. K. and Werden, J. E., Environment, Comfort, Health, and People, Refrigeration Engineering, February 1956 and Rowley, F. G., Jordan, R. C. and Snyder, W. E., Comfort Reaction of 275 Workers During Occupancy of Air Conditioned Offices, Transactions of the American Society of Heating and Ventilating Engineers, Vol. 53, 1947.
1960	77.6 F DBT 30% RH 76.5 F DBT 85% RH	77	Koch, W., Jennings, B. H. and Humphreys, C. M., Sensation Responses to Temperature and Humidity Under Still Air Conditions in the Comfort Range, Transactions of the American Society of Heating, Refrigerating and Air Conditioning Engineers, Vol. 66, 1960.
1965	73-77 DBT less than 60% RH	73-77	ASHRAE Standard
1966	77 F DBT 70% RH 79.5 F DBT 20% RH	78	Nevins, R. G., Rohles, F. H., Springer, W. E., and Feyerherm, A. M., A Temperature Humidity Chart for Thermal Comfort of Seated Persons, Transactions of the American Society of Heating, Refrigerating and Air Conditioning Engineers, Vol. 72, Part 1, 1966.

Envelope (MCE). The slightly modified MCE is shown in Figure 1 as it appears on the New ASHRAE Comfort Chart in the 1972 ASHRAE Handbook of Fundamentals [11]. It is the quadrilateral area called the KSU-ASHRAE Comfort Envelope. The MCE was first used to determine the effects of age on requirements for thermal comfort [12]. This will be discussed in depth later. The comfort zone of the now outdated ASHRAE Standard for Thermal Comfort 55-66 is also shown in Figure 1. The newest ASHRAE comfort envelope, that defined by ASHRAE Comfort Standard 55-74, is shown in Figure 2. The corner points are defined to be adjusted dry bulb temperatures ($t_{adj\ db}$) of 71.5F and 77.6F at a vapor pressure of 14 mmHg and 72.6F and 79.7F at 5 mm Hg. Adjusted dry bulb temperature is defined as the arithmetic average of dry bulb temperature and mean radiant temperature.

The results of the work done by Gagge, Stolwijk, and Nishi [13] was the development of a New Effective Temperature scale (ET*). This index has been rationally derived from a physiological model describing man's heat exchange with the surrounding environment. The New Effective Temperature scale is defined to be the dry bulb temperature at the intersection of the loci of constant skin wettedness due to regulatory sweating with the 50% relative humidity line on the psychrometric chart. Since the New Effective Temperature scale was proposed in 1971, it was also included on the New ASHRAE Comfort Chart, Figure 1. The book Psychrometric Tables for Human Factors Research by Woods and Rohles [14] is a handy companion to the New ASHRAE Comfort Chart. The book contains tabulated values of psychrometric properties as well as predicted physiological and affective responses of sedentary humans.

More recently, Gagge and his co-workers [15] have proposed a Standard Effective Temperature (SET*) which would express thermal comfort in terms

THIS BOOK CONTAINS NUMEROUS PAGES WITH DIAGRAMS THAT ARE CROOKED COMPARED TO THE REST OF THE INFORMATION ON THE PAGE.

THIS IS AS RECEIVED FROM CUSTOMER.

ILLEGIBLE DOCUMENT

THE FOLLOWING DOCUMENT(S) IS OF POOR LEGIBILITY IN THE ORIGINAL

THIS IS THE BEST COPY AVAILABLE

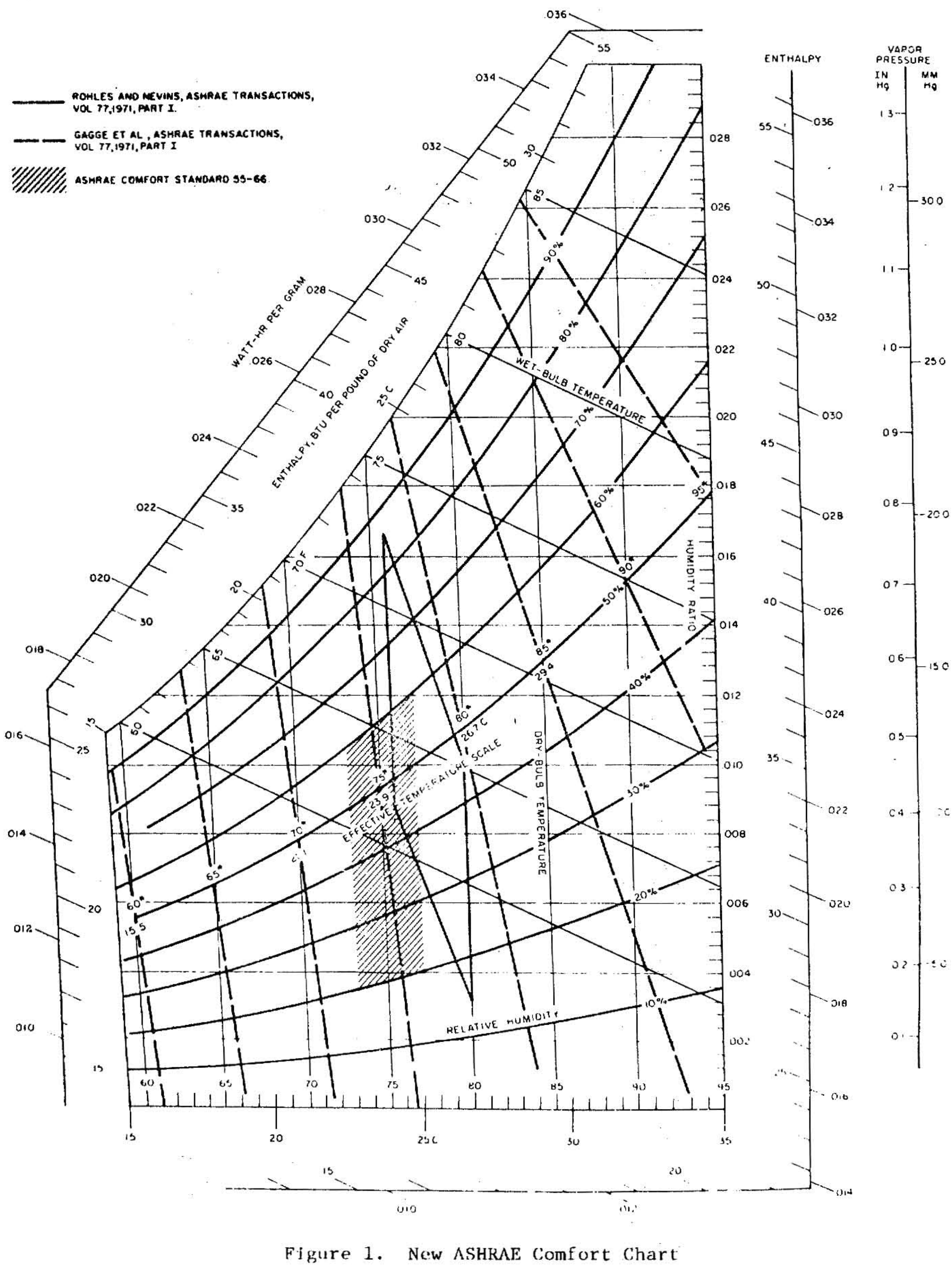


Figure 1. New ASHRAE Comfort Chart

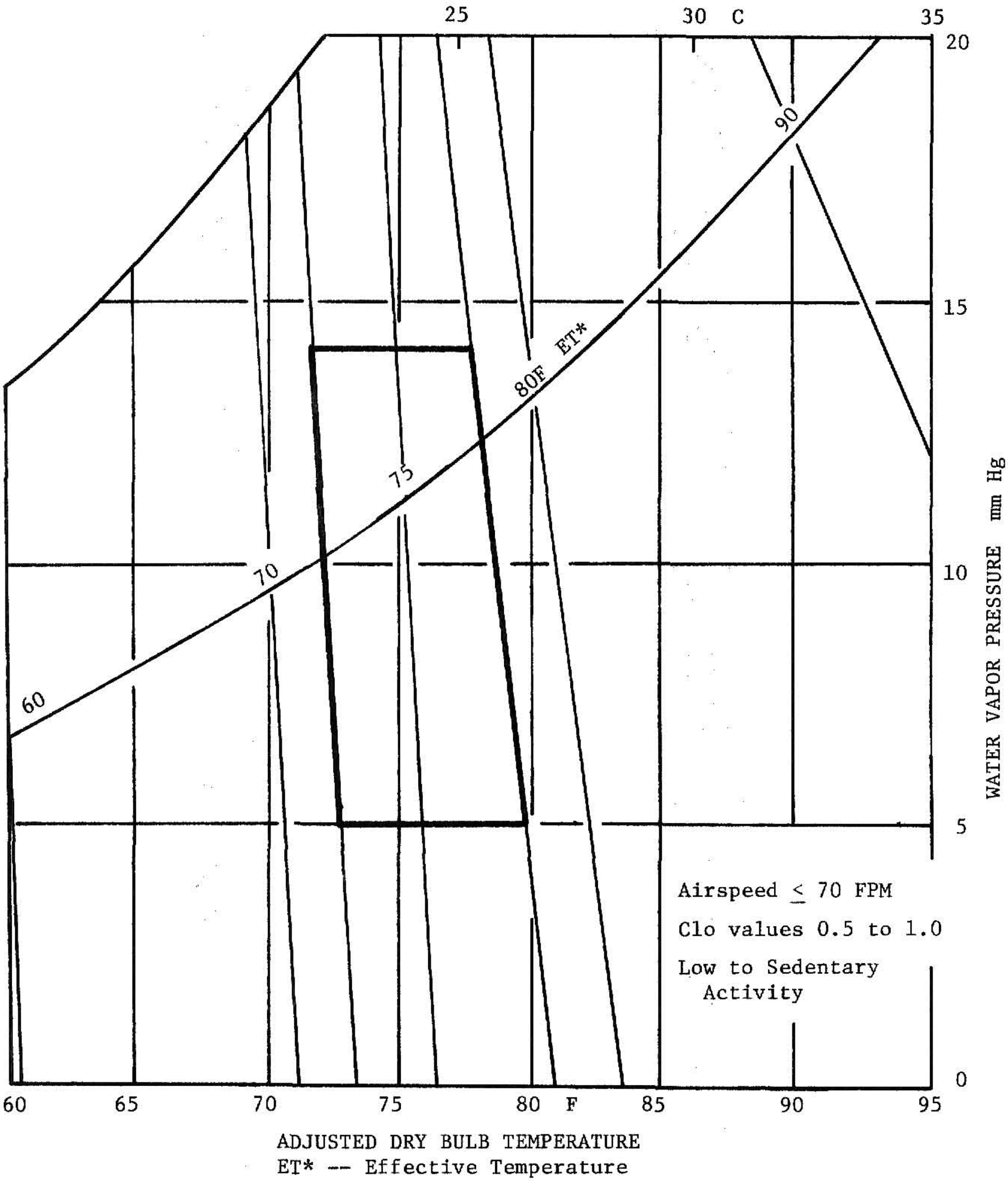


Figure 2. Comfort Envelope -- ASHRAE Standard 55-74

of standard test coefficients. The SET* index would define one's thermal heat exchange with some environment as being equivalent to the same heat exchange in a standard test environment--essentially the ET* of a standard test environment.

Currently Rohles, Hayter and Milliken [16] have used a spline technique, which was discussed in an earlier paper by Rohles [17], to develop a series of equations to predict thermal sensation from the New Effective Temperature.

With this general background about the concept of thermal comfort and some of the major developments in the field, the specific topic of thermal comfort as it relates to the aged follows easily.

THERMAL COMFORT AND THE ELDERLY

The first attempt at predicting a comfortable thermal environment for the elderly was part of a study done by Springer et al. [18] to determine the effect of floor surface temperature on thermal comfort. It was found that with an ambient air temperature of 80F, floor temperatures as high as 85F did not cause serious discomfort among the elderly males (mean age of 71 years) and elderly females (mean age of 68 years).

In a 1969 study done by Rohles [19], 64 elderly subjects, 22 males (mean age 75.7) and 42 females (mean age 74.6), were mailed temperature preference questionnaires. The subjects were asked to classify dry bulb temperatures ranging from 32F to 110F in 2F increments as being cooler-than-comfortable, comfortable, or warmer-than-comfortable for their normal activity level and clothing worn about their residence. They were also supposed to indicate the manner in which they would adjust the thermostat setting for each of the temperature conditions--turn it up, turn it down or leave it alone. The temperatures deemed comfortable resulted in a mean temperature of 74.9F. Although relative humidity was not controlled as in previous laboratory tests with college students [19], Rohles concludes that the results seem to indicate very little difference as far as dry bulb temperature is concerned.

From comfort studies done at the Technical University of Denmark in 1970, Fanger [7] reports an identical neutral temperature of 78.3F for a group of 128 Danish college age persons (mean age of 23.1) as well as for a group of 128 elderly Danish persons (mean age of 68.0). The test was carried out under the following conditions: sedentary activity, light standard clothing (0.6 clo), relative airspeed less than 20.0 FPM, relative humidity of 50% and mean radiant temperature equal to air temperature. Fanger concludes that age seems to play very little importance in determining preferred comfort conditions.

A laboratory study was done by Rohles and Johnson [12] in 1972 in which 104 elderly subjects (mean age 74) participated. Their comfort responses to 15 conditions in the modified Modal Comfort Envelope (KSU-ASHRAE Comfort Envelope) were elicited. This was the first use of the MCE. It was concluded from the study that age did not effect the thermal sensation when measured under the conditions within the Modal Comfort Envelope.

Fanger [20] has indicated that the results of a 1972 study at the Technical University of Denmark in which 16 elderly subjects participated (mean age 84), show that a mean ambient temperature of 77.7F is preferred.

The 1967 ASHRAE Guide and Data Book [21] states, "all men and women over 40 years of age prefer a temperature for comfort 1.0 degree Effective Temperature (ET) higher than that desired by persons below this age". However, results of studies discussed above offer evidence to the contrary. Fanger [20] suggests that the lower metabolism in elderly people might be compensated for by a lower evaporative loss. This could explain why thermal preference seems unaffected by age. Rohles [19] suggests that previous findings should be supplemented with experimental data.

Laboratory studies such as those just described have attempted to identify the entire range of temperature and humidity conditions that the largest percent of elderly people find comfortable. However, the results shed no light on the thermal conditions that exist in the homes and apartments of the elderly and whether or not they find these conditions to be comfortable. This study is the first attempt at determining thermal comfort criteria by actually measuring the thermal environmental conditions that exist in the homes of a representative number of elderly. The data from this sample will be plotted on a psychrometric chart and compared to current design criteria.

CHAPTER TWO

PROJECT DESCRIPTION

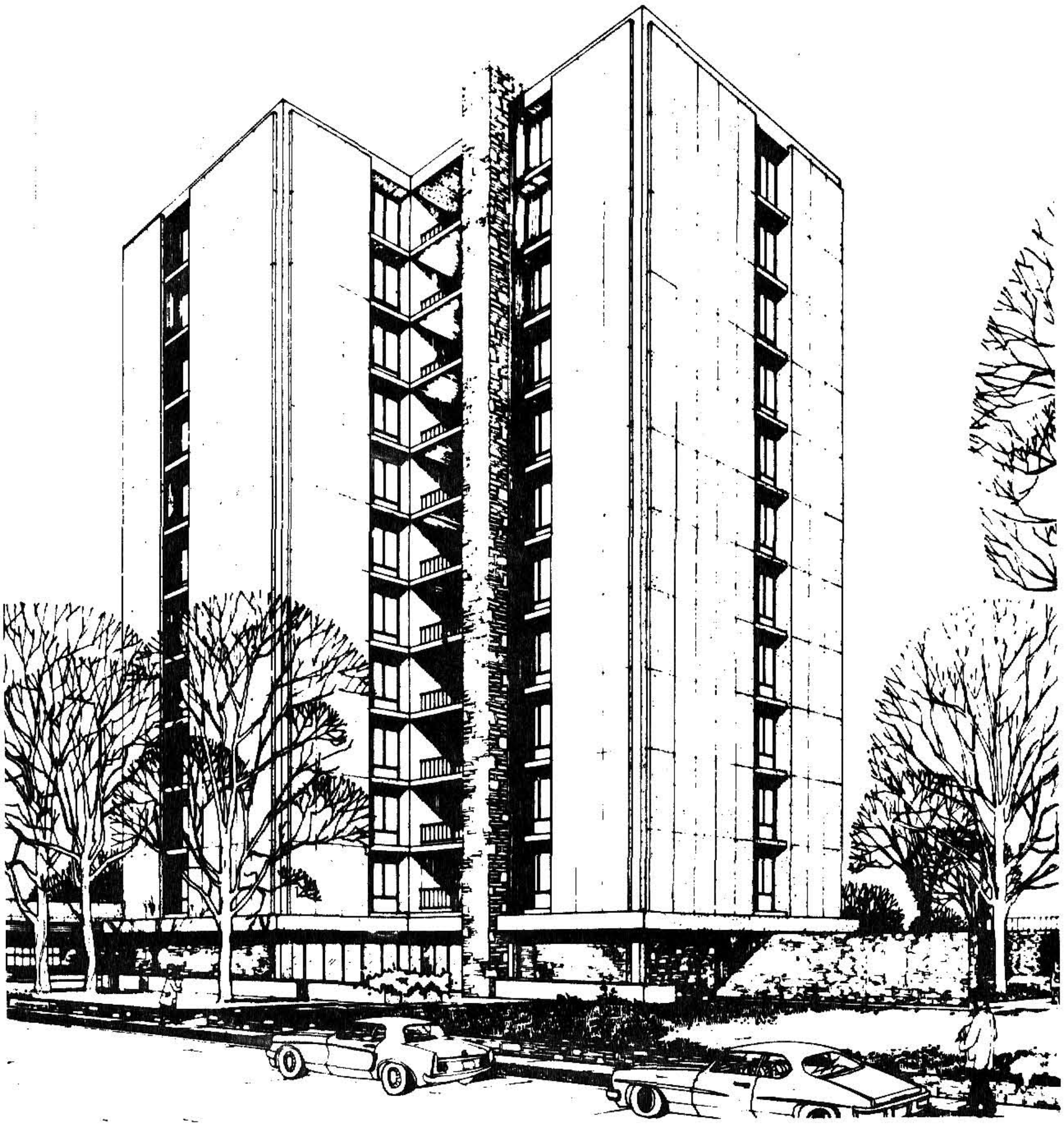
FACILITIES

An apartment-type complex for the elderly was chosen as the test facility. This was done in order to maintain uniformity among as many uncontrollable variables as possible, while at the same time enabling one to obtain a representative sample of thermal environmental conditions. In choosing this kind of living facility, such variables as type of building construction, methods of heating and cooling and wall colors would be identical.

With the cooperation of the Manhattan Housing Authority, the Apartment Tower, see Figure 3, located at 300 North Fifth in Manhattan, Kansas, was chosen for the study. It is a public housing project managed by the Housing Authority of the City of Manhattan with funds provided through guarantees from the federal government.

Designed especially for persons over 62, the Apartment Tower is a 12 story structure with 88 apartments. Figure 4 shows the general floor plan consisting of eight apartments per floor, on floors two through 12. Apartments labeled A, C, E, G and H in Figure 4 are efficiency apartments. The floor plan of these apartments is diagrammed in Figure 5. The floor plan of the one bedroom apartments, those labeled B, D and F, is shown in Figure 6.

The exterior walls of the tower are constructed of four inch nominal thickness split rib concrete block, one inch nominal thickness rigid styrofoam insulation and four inch nominal thickness concrete block. The floors are eight inch reinforced concrete with carpet and carpet pad. The interior walls between apartments are constructed of three inch metal studs with doubled 1/2" fire code sheet rock. The air cavity inside the wall is filled



The Apartment Tower

Figure 3. The Apartment Tower -- Public Housing for the Elderly

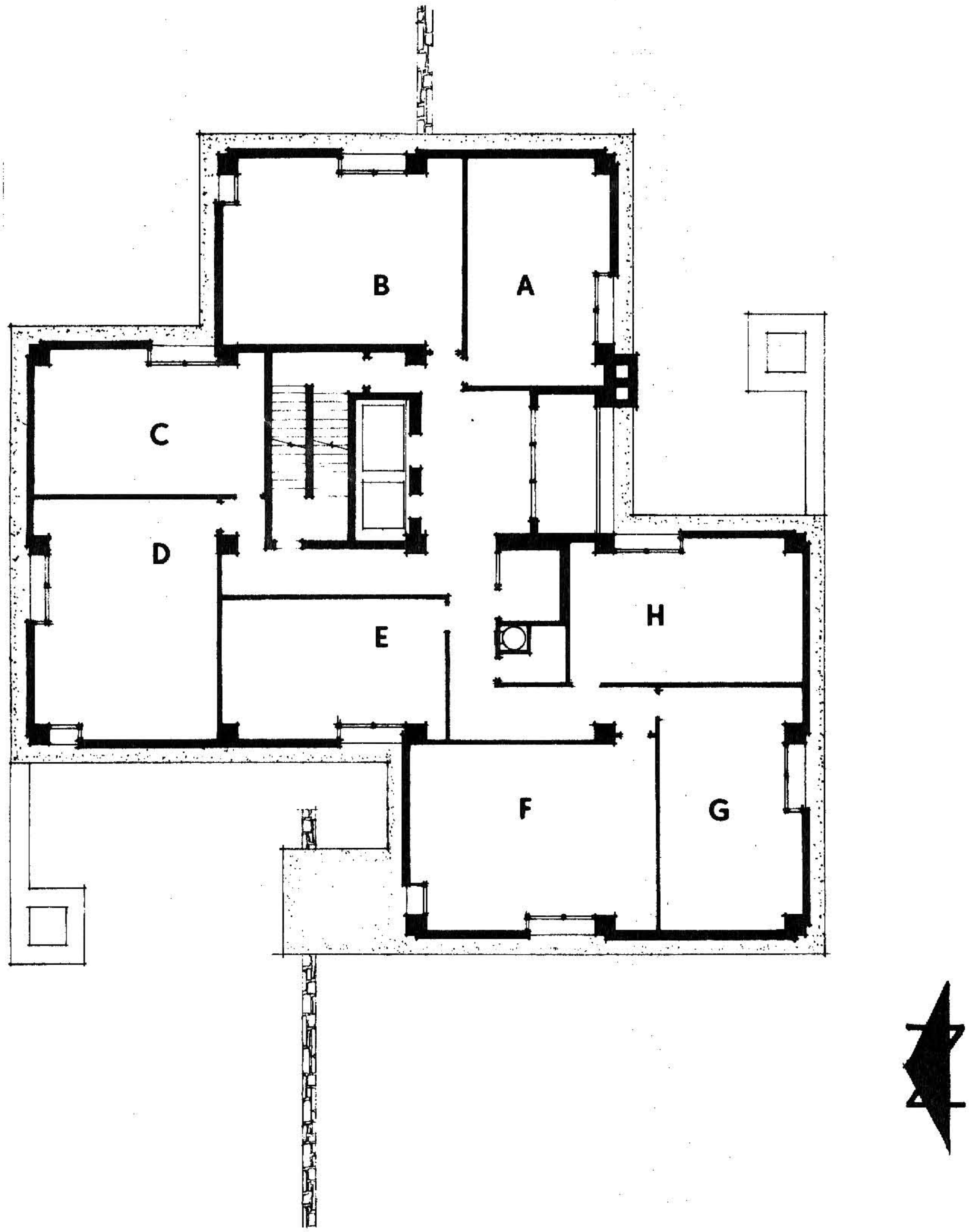


Figure 4. Schematic Floor Plan -- Living Units, Floors 2-12

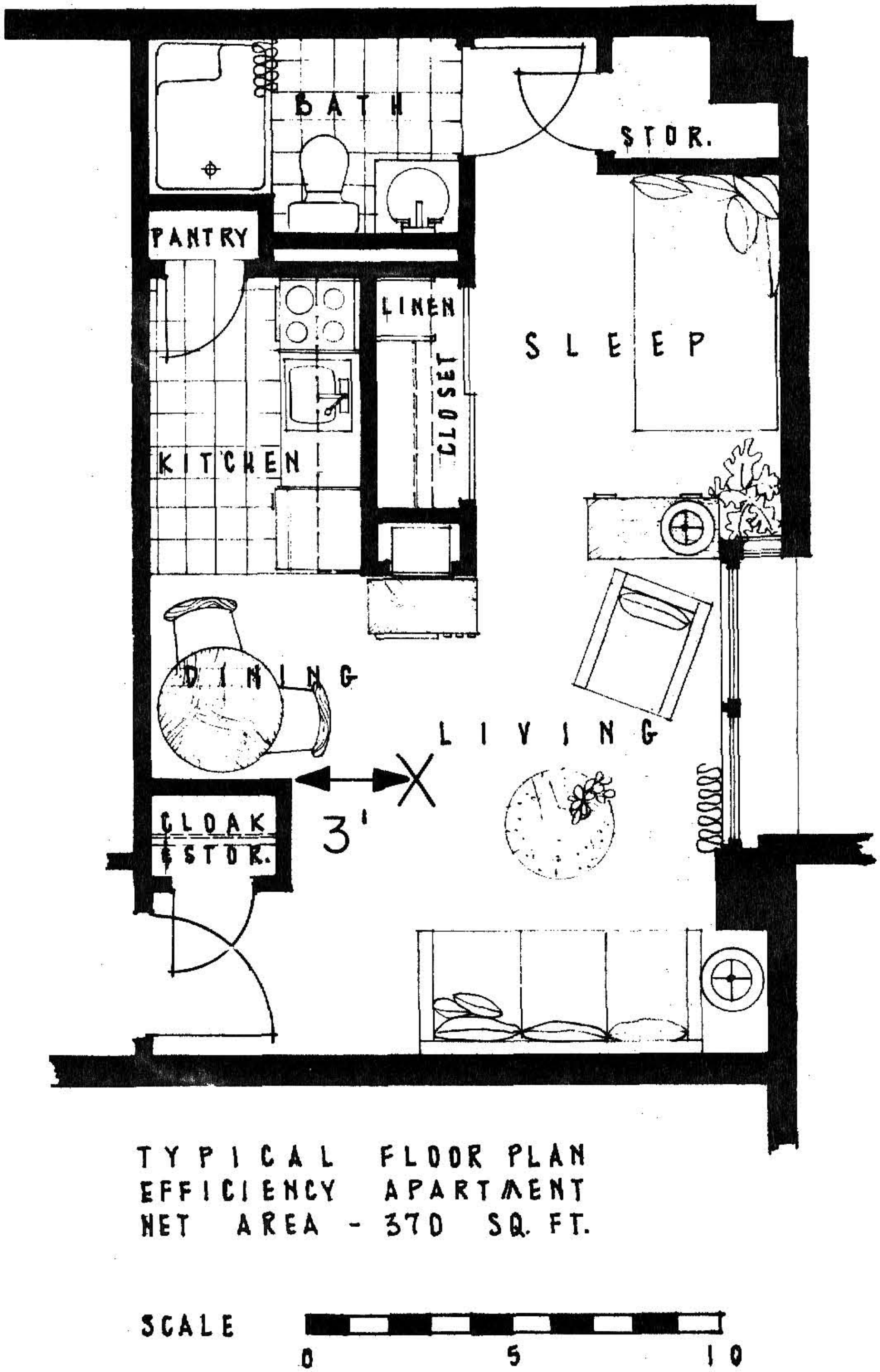


Figure 5. Floor Plan for Efficiency Apartments

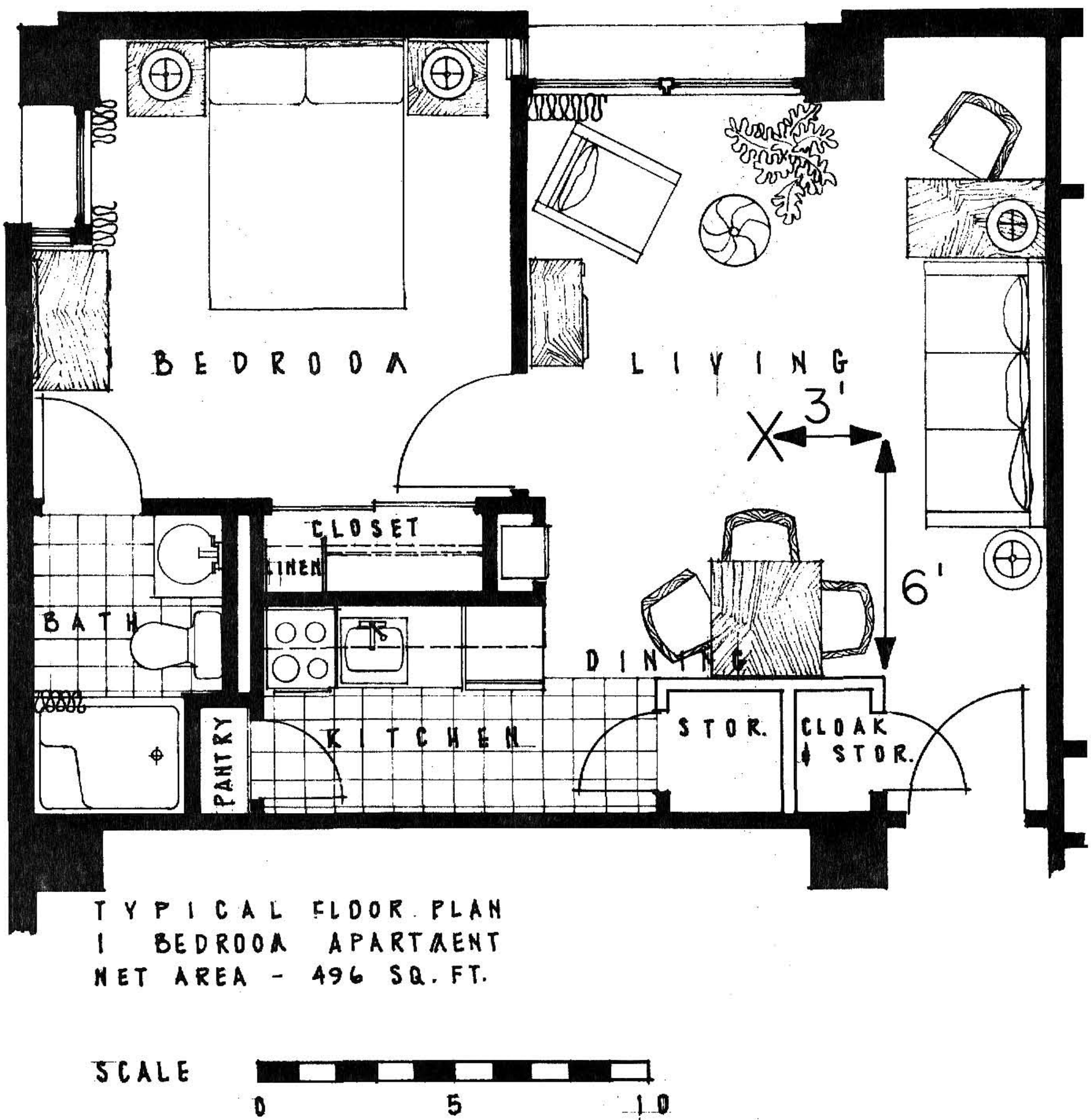


Figure 6. Floor Plan for One-Bedroom Apartments

with sound batting. Windows are 5/16" double strength single pane glass with aluminum clad wood frames that are weather caulked with butyl rubber.

The temperature of each individual apartment may be controlled by means of a forced air fan-coil unit with a thermostat and three speed fan. During the heating season, hot water provided by a 600,000 BTUH nominal water heater is circulated through the central piping system. A 63.5 ton chiller provides 250 gpm of chilled water which is circulated through the central piping system during the cooling season.

The fan-coil unit uses 100% recirculated air. There are, however, exhaust fans in the kitchen and bathroom. Infiltration is relied on to provide fresh air and make-up air for that which is exhausted.

SUBJECTS

With permission of the Manhattan Housing Authority, letters announcing a planned thermal comfort study were distributed to the residents of the Apartment Tower. The residents were invited to attend an orientation meeting in the Community Room of the Apartment Tower to see how the data would be obtained and to have any questions answered concerning the project. A schedule of time slots was made available at the meeting, enabling those who wanted to participate to sign up. There was very poor attendance at this meeting, so those who did not attend were personally contacted and invited to attend a second meeting. This follow-up meeting proved more successful and resulted in a total of 34 residents wishing to participate. This group included two married couples and 30 people living alone.

Of the 34 participants, four were males ranging in age from 63 years to 86 years with a mean age of 74.0 years. Thirty female residents participated, ranging in age from 62 years to 90 years. The mean age of the women was 74.2 years. The mean age of the group of subjects as a whole was 74.2 years. The female to male ratio of 7.5:1 for the experimental group compared with the national average of 1.4:1 for persons over 65 years of age [22].

Specific questions about the socioeconomic backgrounds of the participants were not asked. However, informal conversations during the data taking sessions indicated the following general information. Most of the people had come from small towns and rural areas. For the most part the subjects could have been classified in the middle-income bracket during their working years before retirement. It seems that most of the participants had been raised in Kansas or had lived in Kansas for an extended period of time. All of the participants were in reasonably good health and were able to do their own shopping, cooking, housecleaning and other light chores.

As mentioned earlier, the clothing insulation value (I_{cl}) for the ensemble one is wearing is an important factor influencing his/her feelings of comfort. Therefore, it was felt necessary to have an assessment of the type of clothing being worn by the elderly and the corresponding insulation value. With the help of Deanna Munson, Instructor of Clothing and Textiles at Kansas State University, a list was composed of different items of clothing which would typically be worn by the elderly. For example, one item listed was a women's dress which could be classified as being sleeveless, short sleeved or long sleeved and its weight could be classified as light (a cotton or synthetic) or heavy (a wool or thickly woven article). A sample of the data sheet which includes the clothing survey is found in Appendix A. The Thermal Insulating Values (TIV) for the resulting ensembles worn by the subjects during and preceding the data taking session were assigned with the aid of the findings reported in Seppanen, et al. [16]. Seppanen and his co-workers used a heated copper manikin dressed in typical clothing ensembles and at equilibrium with its surroundings to determine the thermal insulating values. The results of this study are tabulated in Appendix B. As an example, if during the testing one of the elderly subjects was wearing a light weight, short sleeved blouse and a light weight skirt, the ensemble was given an insulation value of 0.33 clo corresponding to the women's ensemble number 60 in Appendix B. One clo unit is defined to be 0.88 (sq.ft.)(hr.)(F)/BTU. Some of the women's slack outfits were best approximated by ensembles classified as typical men's ensembles in which case they were assigned the insulation value of the man's ensemble. Seppanen and his co-workers also reported that the type of underwear worn by women has relatively little effect on thermal insulating values. Therefore, to avoid embarassment, questions concerning undergarments were not asked and it was assumed the subjects were wearing some sort of typical underwear. The range of thermal insulating values for the ensembles worn by the 34 subjects as a whole ranged from 0.21 clo to 1.00 clo with an average value of 0.49 clo. If the high and low extremes are excluded, the insulating values then range from 0.32 clo to 0.71 clo. The insulating values for the ensembles worn by the four male subjects ranged from 0.51 clo to 0.65 clo with an average of 0.60 clo, while the corresponding insulating values for the ensembles worn by the 30 female subjects ranged from 0.21 clo to 1.00 clo with an average value of 0.48 clo.

The activity level of the subjects could be classified as sedentary. For the most part, the subjects had been sitting prior to the testing and remained so during the testing period.

ENVIRONMENTAL TESTING INSTRUMENT

The Apartment Tower comfort study was the first use of the KSU Environmental Testing Instrument (ETI) shown in Figures 7 and 8. The Environmental Testing Instrument was one of two alternative approaches studied by Guy [24] to develop an instrument to collect environmental data and evaluate it in a way to give a measure of the thermal quality of an interior environment.

Built by Institute for Environmental Research engineers with support from ASHRAE, the basic function of the prototype instrument is to collect environmental data (airspeed, relative humidity, dry bulb temperature and globe temperature) and to evaluate it to determine whether or not the given interior environment satisfies the requirements of ASHRAE Comfort Standard 55-74. A report describing this function of the instrument and its operation is in the process of being written by Turnquist and Volmer [25] and will be published by the Institute of Environmental Research.

An additional feature, the capability of the instrument to provide a direct read out of the values for dry bulb temperature (t_{db}), globe temperature (t_g), local airspeed (VEL) and relative humidity (RH) makes it valuable as a measurement tool as well as an evaluation instrument. For the study described in this thesis, the Environmental Testing Instrument was used as a measurement tool to measure the environmental variables listed above. The values of the environmental variables were read directly from the instrument and recorded on a data sheet, a sample of which is shown in Appendix A. A brief description of the four sensors and their associated analog circuits follows.

The thermocouple output of the airspeed probe, shown in Appendix C

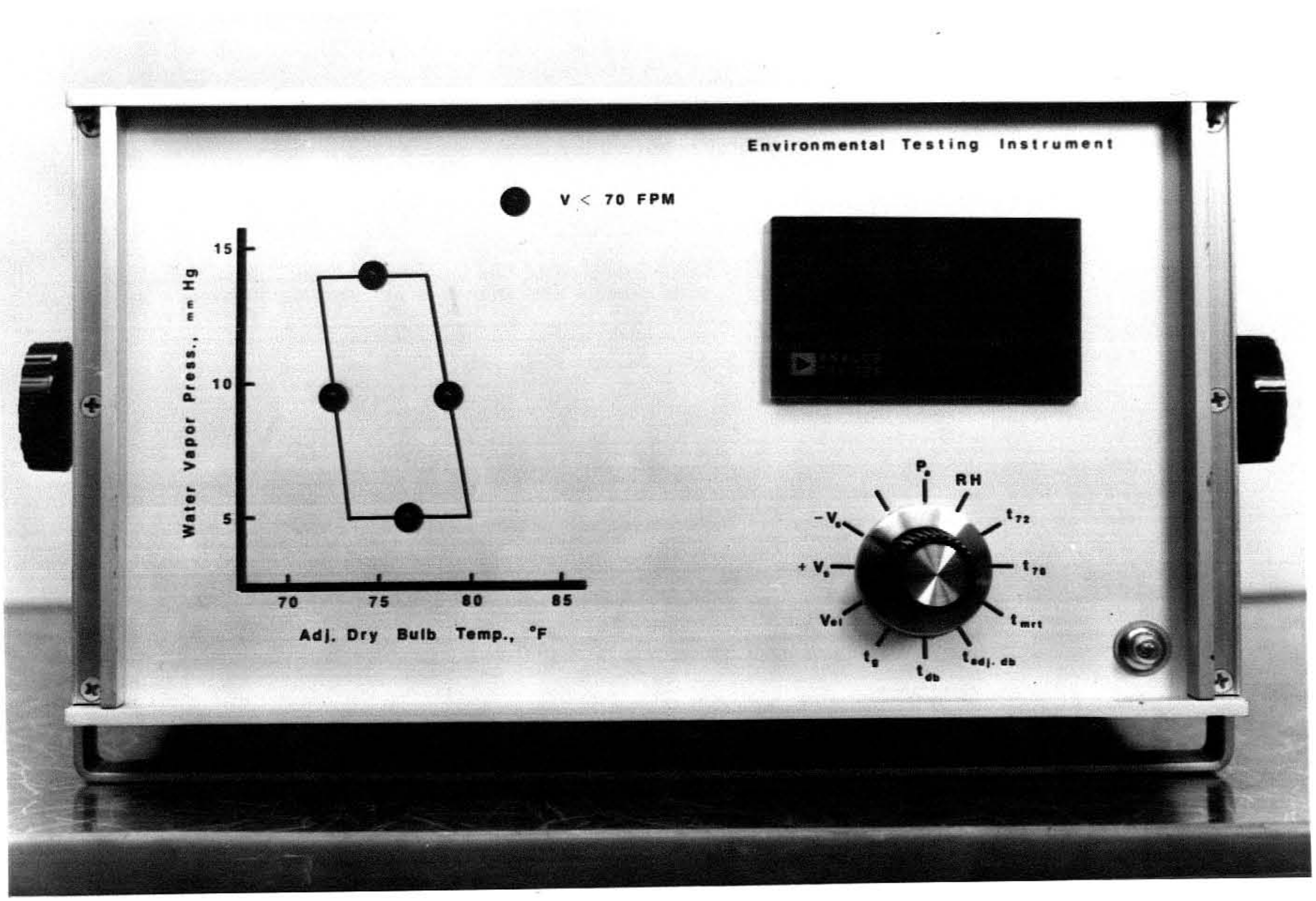


Figure 7. Close-up of Front Panel of Environmental Testing Instrument

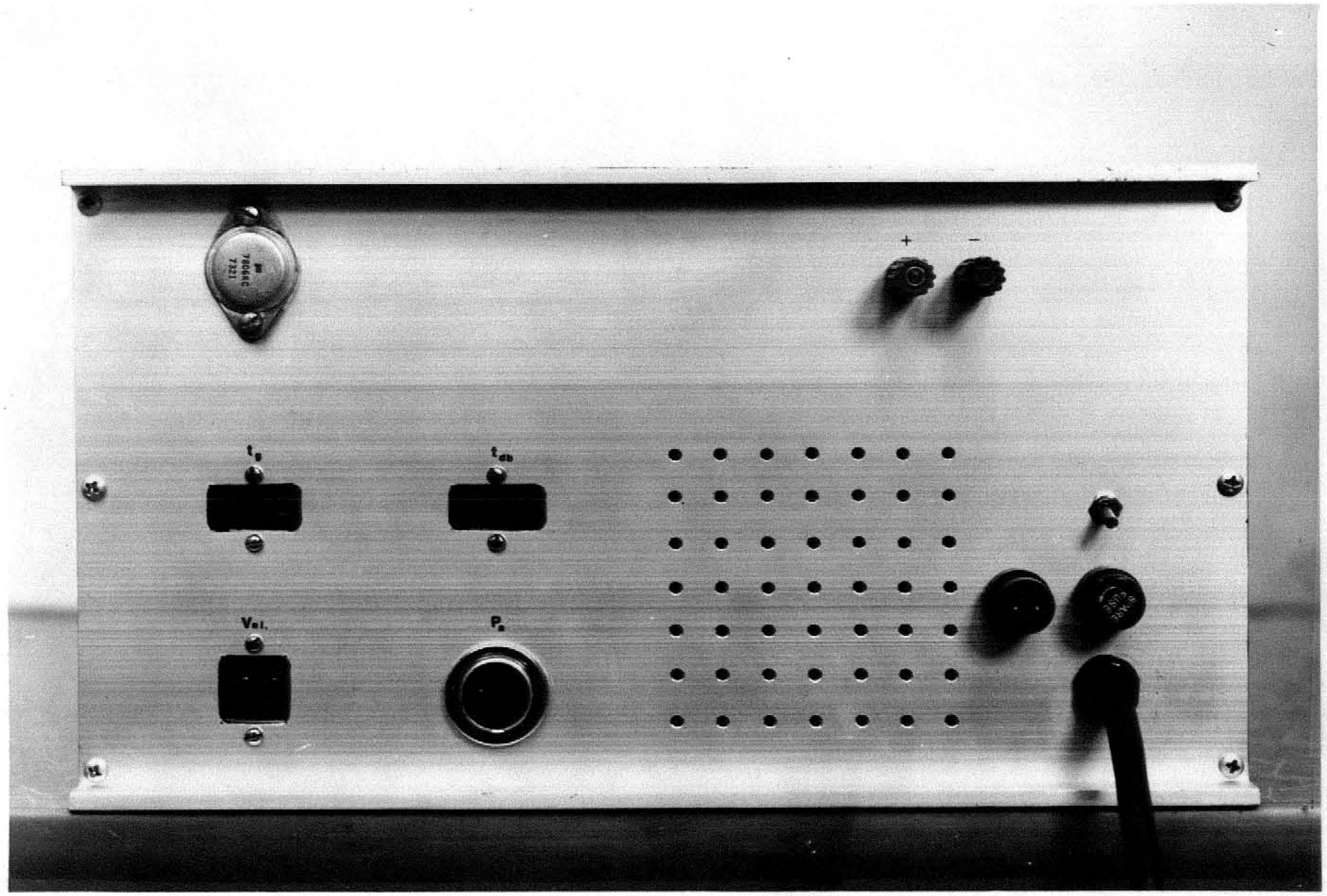


Figure 8. Close-up of Rear Panel of Environmental Testing Instrument

with the other sensors to be described below, is the input to an analog circuit which calculates the local airspeed. For example, with the selector switch on the front panel of the ETI set to VEL, the output of the airspeed circuit for a calculated airspeed of 50.0 FPM would be indicated as 50.0 millivolts on the digital panel meter (see Figure 7).

Dry bulb temperature is calculated by means of an analog circuit which converts the emf output of a Yellow Springs Thermilinear thermistor to a DC voltage proportional to temperature. The thermistor for dry bulb temperature is enclosed in an epoxy-sealed probe exposed to ambient room air. With the selector switch set to t_{db}, an output of 75.8 millivolts would be indicated by the digital panel meter for a calculated dry bulb temperature of 75.8F.

Globe temperature is calculated by an analog circuit identical to that for dry bulb temperature. As defined by ASHRAE Standard 55-74, globe temperature is the equilibrium temperature at the center of a six-inch diameter thin-walled sphere. The surface of the globe is specified to be pink in color (No. 11-B-2 from the Marez and Paul Color Dictionary, McGraw-Hill, 1951). This temperature is sensed by a thermistor, identical to that for dry bulb temperature, located at the center of a six-inch copper sphere. For the selector switch set to t_g, the digital panel meter would indicate 77.9 millivolts for a calculated globe temperature of 77.9F.

The relative humidity circuit converts impedance changes in an electro-hygrometric plastic wafer into a voltage proportional to relative humidity. These changes in impedance are caused when moisture is gained or lost by the plastic sensing element by the mechanism of adsorption. By setting the selector switch to RH, the digital panel meter would indicate 50.5 millivolts for a calculated relative humidity of 50.5%.

The error specifications for the measured variables just described are included in the uncertainty analysis of Appendix F.

PROCEDURES

The Apartment Tower comfort study was conducted during the final two weeks of September, 1974. The weather had been cool so the central piping system of the Apartment Tower was circulating hot water.

The testing sessions, conducted between the hours of 8:00 a.m. and 5:00 p.m., required 30 minutes for each. The tests were conducted in the following manner.

The subjects who had signed up at the orientation meetings were met at their apartment at the agreed upon time. The Environmental Testing Instrument was wheeled into their apartment and the test stand holding the probes, see Figure 9, was located in a prescribed location. This location is marked by an X on the floor plan of the efficiency and one bedroom apartments shown previously in Figures 5 and 6 respectively. The airspeed and dry bulb temperature probes located at the top of the test stand, Figure 9, were approximately three feet from the floor.

Once the test stand was located, the Environmental Testing Instrument was switched on. After a fifteen minute period to allow the sensors to reach equilibrium with the room conditions, the measured values of the four environmental variables described previously, dry bulb temperature, globe temperature, airspeed and relative humidity, were recorded on a data sheet, Appendix A. The subject was then handed a nine point comfort ballot, Figure 10, and asked to describe which adjective best described their feelings. The subjects were not informed about the temperature or humidity of their apartment until after they had voted. This was done to prevent any preconceived ideas about a "comfortable temperature" from interfering with their true thermal sensations at the moment. In the two cases where married

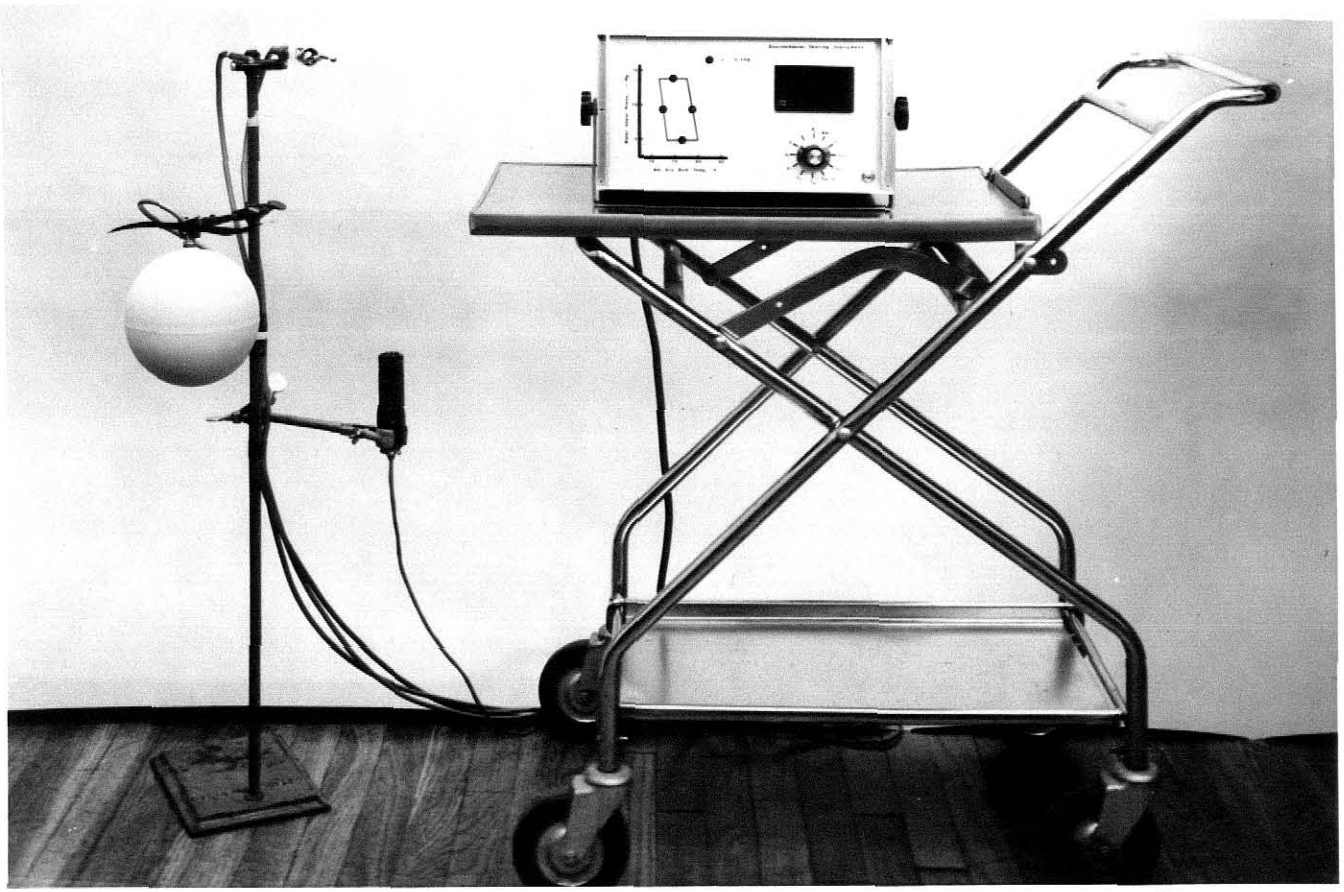


Figure 9. Environmental Testing Instrument -- Test Arrangement

WHICH ADJECTIVE CORRECTLY
DESCRIBES HOW YOU FEEL
RIGHT NOW?

9. VERY HOT
8. HOT
7. WARM
6. SLIGHTLY WARM
5. NEUTRAL
4. SLIGHTLY COOL
3. COOL
2. COLD
1. VERY COLD

FIGURE 10. Thermal Comfort Ballot

couples participated, the comfort vote of a spouse was not discussed or revealed until both had indicated their feelings. The comfort votes were also recorded on the data sheet.

The articles of clothing being worn by the subject were recorded on the data sheet during the fifteen minutes of informal conversations preceding the actual test readings.

Upon completion of the testing sessions, a computer program, listed in Appendix D, was used to reduce the data. With values for globe temperature, dry bulb temperature, airspeed and relative humidity available, it was possible to calculate adjusted dry bulb temperature, $t_{adj\ db}$, and vapor pressure, P_a. These are the coordinates of the graph outlining the comfort envelope in ASHRAE Standard 55-74. They are also the variables that were plotted in developing the thermal comfort data of this study. The equations implemented in the program to calculate these variables are described below.

Vapor pressure was calculated using the following relationship:

$$P_a = RH \times P_s \qquad (1)$$

where P_s is the saturated vapor pressure. Saturated vapor pressure was determined using the steam tables after the dry bulb temperature was determined. The measured values of relative humidity were corrected per calibration data before being used in the calculations.

Adjusted dry bulb temperature is defined by ASHRAE Standard 55-74 as the arithmetic average of mean radiant temperature (t_{mrt}) and dry bulb temperature. Mean radiant temperature is defined in the same standard by the following equation:

$$t_{mrt} = (1.0 + 0.157\sqrt{VEL})\ (t_g - t_{db}) + t_{db} \qquad (2)$$

where the units for VEL are feet per minute and t_{mrt}, t_g and t_{db} are in degrees Fahrenheit. The measured values of airspeed were corrected per calibration data before being used in the calculations. It follows that the equation for adjusted dry bulb temperature would be:

$$t_{adj\ db} = \frac{t_{mrt} + t_{db}}{2} \quad . \tag{3}$$

The numerical results for each subject may be found in Table A5 in Appendix E. The results are presented graphically in the next section along with several conclusions.

CHAPTER THREE

DISCUSSION OF RESULTS

DATA ANALYSIS

The psychrometric chart, a graphical representation of the thermodynamic properties of moist air, continues to be an important tool in the study of thermal comfort. Houghten and Yaglou [3] chose the "psych chart" as the format for presenting their "lines of equal comfort" in 1923. ASHRAE has traditionally used this type of chart for describing thermal comfort criteria. The New ASHRAE Comfort Chart in current use is diagrammed on a chart whose coordinates are dry bulb temperature and partial vapor pressure of water.

The results of this study are presented graphically on the psychrometric chart of Figure 11. The coordinates of adjusted dry bulb temperature in degrees Fahrenheit and partial vapor pressure of water in millimeters of mercury were chosen in order to be consistent with the Comfort Envelope of ASHRAE Standard 55-74. Each data point is identified by the symbol for the corresponding comfort vote expressed by the test subject.

Since there was no provision for humidity control in the Apartment Tower system, Figure 11 is not intended to relate the thermal comfort votes to the observed conditions of water vapor pressure. Recall, however, that the Apartment Tower residents could adjust the temperature of their apartments to a desired condition. Figure 11 is then, an indication of the comfort responses associated with the measured values of adjusted dry bulb temperature and the coincidental water vapor pressure conditions.

Figure 11 indicates that out of the 34 apartments sampled for thermal environmental conditions, 27 of the environments received a neutral vote by the occupant. This is equivalent to saying that the subject was comfortable with the conditions that existed in his/her apartment during

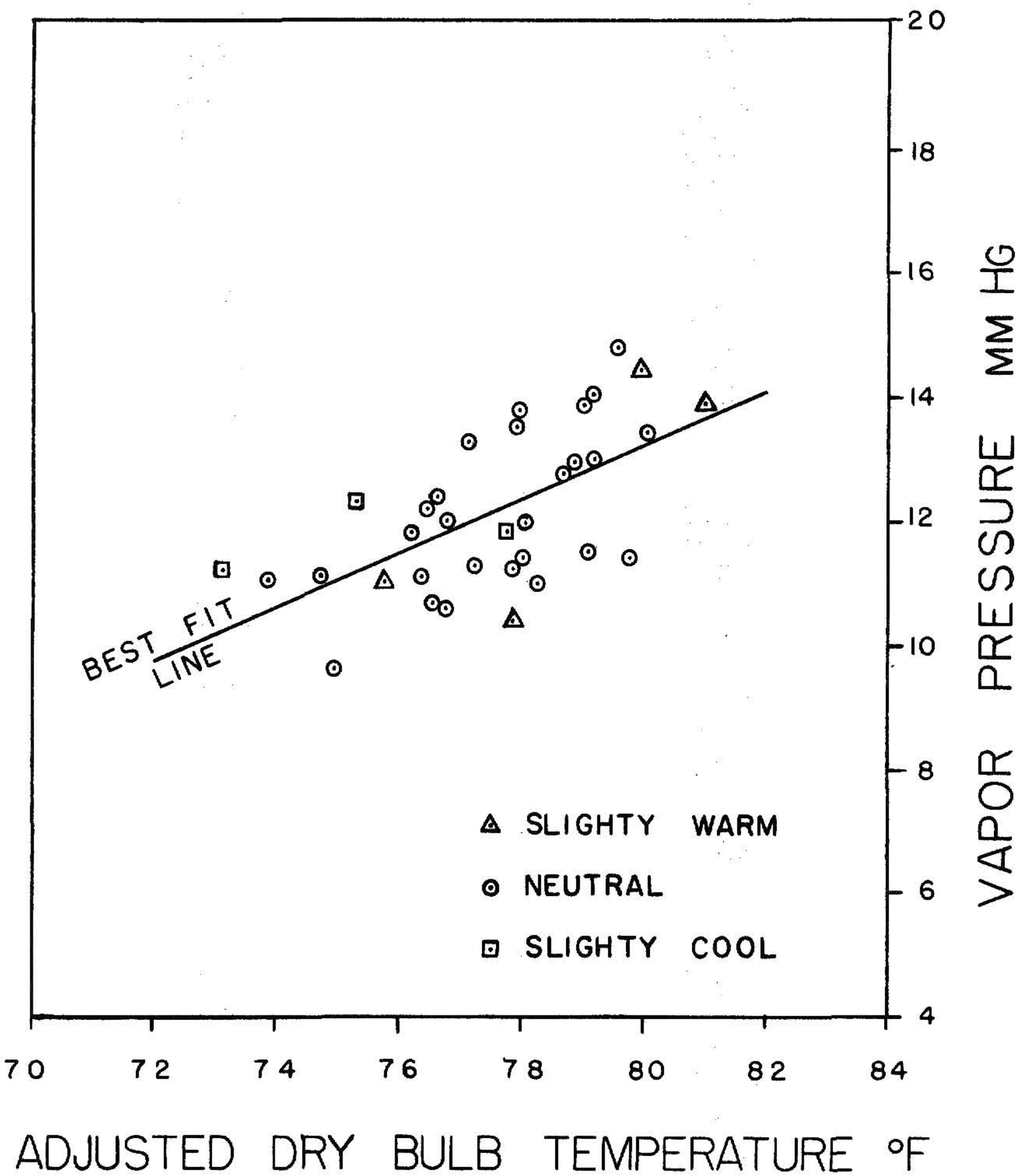


Figure 11. The Apartment Tower Environmental Conditions

the testing period--neither slightly warm nor slightly cool. The mean value of adjusted dry bulb temperature for the 27 environments receiving neutral votes was 77.6F. For the four subjects who indicated that they were slightly warm, the average adjusted dry bulb temperature of their apartments was 78.6F. The mean value of adjusted dry bulb temperature in the apartments whose occupants voted slightly cool was 75.4F. All four male subjects responded to the comfort ballot with neutral votes. The average adjusted dry bulb temperature for their apartments was 78.2F. Twenty-three of the female subjects expressed comfort with the conditions in their apartments. The mean value of adjusted dry bulb temperature was 77.5F.

A linear regression analysis of the data points yielded a "best fit" line with a positive slope of 0.44 mm Hg/°F. That is, lower vapor pressures were encountered at lower adjusted dry bulb temperatures and higher vapor pressures were observed at higher adjusted dry bulb temperatures. This is not intended to say that the general trend for comfort was higher thermostat settings for higher humidities.

The significance of the mean value of 77.6F for adjusted dry bulb temperature in the 27 "neutral environments" can best be illustrated with Figure 12. This figure outlines the KSU-ASHRAE Comfort Envelope plotted on a modified New ASHRAE Comfort Chart. This envelope applies for occupants wearing 0.6 clo to 0.8 clo insulation and for sedentary activity. It applies for environments in which mean radiant temperature is nearly equal to dry bulb temperature. Adjusted dry bulb temperature is equal to dry bulb temperature for this case. Therefore, the temperature scale of Figure 12 was modified to read adjusted dry bulb temperature in order that the 77.6F line might be compared with the KSU-ASHRAE Comfort Envelope.

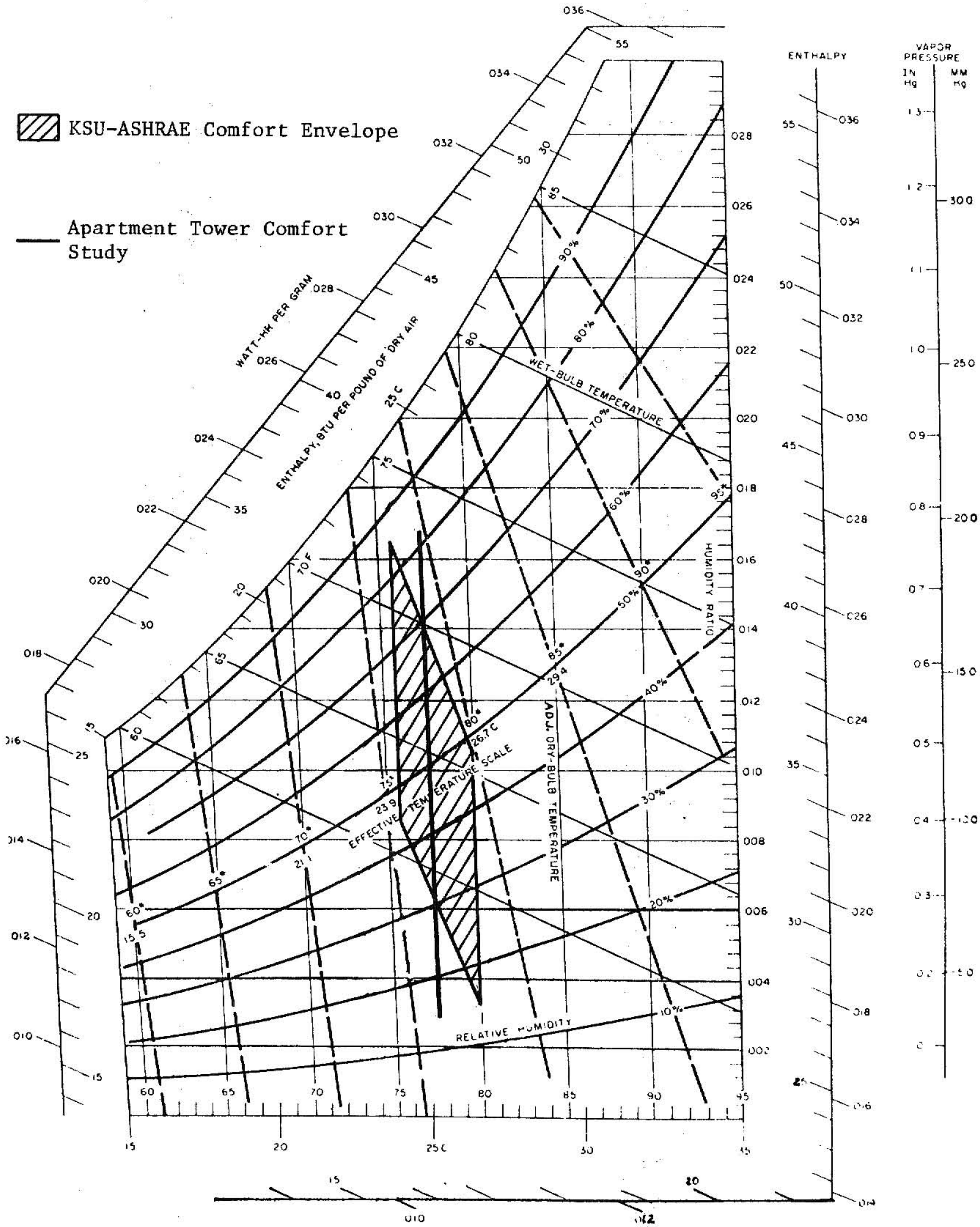


Figure 12. Comparative Comfort Criteria

CONCLUSIONS

As illustrated by Figure 12, the mean value of adjusted dry bulb temperature of 77.6F for the 27 neutral conditions bisects the KSU-ASHRAE Comfort Envelope. This information suggests that the design engineer might expect favorable thermal responses by the elderly to conditions inside the KSU-ASHRAE Comfort Envelope. Since college student data was used to develop the KSU-ASHRAE Comfort Envelope, the evidence of Figure 12 supports the now generally accepted conclusion that thermal comfort is relatively unaffected by age [9].

An unexpected finding of this project was the low clothing insulation values. As mentioned previously, excluding the high and low values, the range was from 0.32 clo to 0.71 clo. This contrasts with the 0.6 clo to 0.8 clo range of the KSU-ASHRAE Comfort Envelope and the 0.5 clo to 1.0 clo of ASHRAE Standard 55.74. This finding suggests that further study be directed toward determining the amount and type of clothing people actually wear about their residences (as opposed to office attire).

As an initial investigation, this project has not explored all the possible environmental conditions that are likely to exist in apartments of the elderly nor has it been an attempt to. For example, the narrow range of relative humidity might be broadened by data collected during summer and winter months. Although the results of this project seem to agree with existing standards, the general conclusions could be strengthened by studying a larger sample with data obtained during different seasons of the year.

LIST OF REFERENCES

1. ASHRAE Standard 55-74, Thermal Environmental Conditions for Human Comfort. Approved March 1, 1974, American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc., New York, 1974.

2. Rohles, F. H., Environmental Psychology. Psychology Today, June, 1967.

3. Houghten, F. C., and Yaglou, C. P., Determining Lines of Equal Comfort. ASHVE Transactions, 1923.

4. Rohles, F. H., and Nevins, R. G., Thermal Comfort: New Directions and Standards. Aerospace Medicine, 1973, 44.

5. Nevins, R. G., Criteria for Thermal Comfort. Building Research, July-August, 1966.

6. Fanger, P. O., Calculation of Thermal Comfort: Introduction of a Basic Comfort Equation. ASHRAE Transactions, Volume 73, Part II, 1967.

7. Fanger, P. O., Thermal Comfort, Analysis and Applications in Environmental Engineering. Danish Technical Press, Copenhagen, 1970.

8. Rohles, F. H., and Nevins, R. G., Short Duration Adaptation to Comfortable Temperatures. ASHRAE Transactions, Volume 74, Part I, 1968.

9. Rohles, F. H., The Modal Comfort Envelope -- A New Approach Toward Defining the Thermal Environment in Which Sedentary Man Is Comfortable. ASHRAE Transactions, Volume 76, Part II, 1970.

10. Rohles, F. H., Thermal Comfort in Sedentary Man. Paper presented at the Fifth International Congress for Heating, Ventilating and Air-Conditioning, Copenhagen, 1971.

11. Anonymous, ASHRAE Handbook of Fundamentals, Chapter 9, 1972.

12. Rohles, F. H., and Johnson, M. A., Thermal Comfort in the Elderly. ASHRAE Transactions, Volume 78, Part I, 1972.

13. Gagge, A. P., Stolwijk, J. A. J., and Nishi, Y., An Effective Temperature Scale Based on a Simple Model of Human Physiological Regulatory Response. ASHRAE Transactions, Volume 77, Part I, 1971.

14. Woods, J. E., and Rohles, F. H., Psychrometric Tables for Human Factors Research. Institute for Environmental Research Publication 73-02, Kansas State University, 1972.

15. Gagge, A. P., Nishi, Y., and Gonzalez, R. R., Standard Effective Temperature -- A Single Temperature Index of Temperature Sensation and Thermal Discomfort. Thermal Comfort and Moderate Heat Stress, Symposium Proceedings, Building Research Establishment Report No. 2, Garston Watford WDZ 7JR, England, September, 1972.

16. Rohles, F. H., Hayter, R. B., and Milliken, G. A., Effective Temperature (ET*) As a Predictor of Thermal Comfort. Paper to be presented. 1975.

17. Rohles, F. H., The Measurement and Prediction of Thermal Comfort. ASHRAE Transactions, Volume 80, Part II, 1974, in press.

18. Springer, W. E., Nevins, R. G., Feyerherm, A. M., and Michaels, K. B., The Effect of Floor Surface Temperature on Comfort: Part III, The Elderly. ASHRAE Transactions, Volume 72, Part 1, 1966.

19. Rohles, F. H., Preference for the Thermal Environment by the Elderly. Human Factors, 11, 1969.

20. Fanger, P. O., Assessment of Man's Thermal Comfort in Practice. British Journal of Industrial Medicine, Volume 30, 1973.

21. ASHRAE Guide and Data Book, Fundamentals. New York, American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc., 1967.

22. Anonymous, March, 1972 Survey of Bureau of the Census. The 1975 World Almanac and Book of Facts, Newspaper Enterprise Association, Inc., New York, 1974.

23. Seppanen, O., McNall, P. E., Munson, D. M., and Sprague, C. H., Thermal Insulating Values For Typical Indoor Clothing Ensembles. ASHRAE Transactions, Volume 78, Part I, 1972.

24. Guy, H. P., Two Techniques for the Development of an Instrument to Evaluate the Quality of a Thermal Environment, M.S. Thesis, Kansas State University, Manhattan, Kansas, 1973.

25. Turnquist, R. O., and Volmer, R. P., A Description of the KSU Environmental Testing Instrument. Report to be published by the Institute for Environmental Research, Kansas State University, Manhattan, Kansas, 1975.

26. Sprague, C. H., and Nash, R. T., Introduction to Engineering Experimentation. Department of Mechanical Engineering, Kansas State University, Manhattan, Kansas, 1972.

APPENDICES

Appendix A

Sample Data Sheets

Table A1. Sample Data Sheet, Male Subject

THE APARTMENT TOWER COMFORT STUDY
MALE DATA SHEET

NAME	John Doe	AGE	86	DATE	9-24-74	TIME	9:30 a.m.
SUBJECT NUMBER	1	APARTMENT NUMBER	3F	WINDOW EXPOSURE	WEST		

MEASURED VALUES		ADJUSTED VALUES*		CALCULATED VALUES	
VEL	7.0 FPM		9.5 FPM	t_{mrt}	78.8 °F
RH	45.5 %		50.0 %	$t_{adj\ db}$	78.0 °F
t_{db}	77.3 °F	REFERENCE DATA		P_a	12.00 mm Hg
t_g	78.3 °F	P_s	23.99 mm Hg	COMFORT VOTE	5

CLOTHING SURVEY

GARMENT		SLEEVE LENGTH			WEIGHT OF GARMENT	
WOVEN SHIRT	✓	LONG ✓	SHORT	SLEEVELESS	LIGHT ✓	HEAVY
KNITTED SHIRT	✓	LONG	SHORT	SLEEVELESS ✓	LIGHT ✓	HEAVY
JACKET		LONG			LIGHT	HEAVY
SWEATER		LONG	SHORT	SLEEVELESS	LIGHT	HEAVY
BELT						
TROUSERS	✓				LIGHT ✓	HEAVY
OTHER:						

REFERENCE ENSEMBLE NO.† M17 I_{cl} 0.65

*Adjusted per Calibration Data.
†Refers to Ensembles Listed in Table A3.

Table A2. Sample Data Sheet, Female Subject

THE APARTMENT TOWER COMFORT STUDY
FEMALE DATA SHEET

NAME Jane Doe AGE 66 DATE 9-25-74 TIME 3:30 p.m.

SUBJECT NUMBER 17 APARTMENT NUMBER 7F WINDOW EXPOSURE WEST

MEASURED VALUES	ADJUSTED VALUES*	CALCULATED VALUES
VEL 4.0 FPM	6.0 FPM	t_{mrt} 77.1 °F
RH 56.0 %	51.7 %	$t_{adj\ db}$ 76.8 °F
t_{db} 76.4 °F	REFERENCE DATA	P_a 12.04 mm Hg
t_g 76.9 °F	P_s 23.29 mm Hg	COMFORT VOTE 5

CLOTHING SURVEY

GARMENT		SLEEVE LENGTH			WEIGHT OF GARMENT	
DRESS	✓	LONG	SHORT ✓	SLEEVELESS	LIGHT	HEAVY ✓
BLOUSE		LONG	SHORT	SLEEVELESS	LIGHT	HEAVY
JACKET		LONG	SHORT	SLEEVELESS	LIGHT	HEAVY
SWEATER		LONG	SHORT	SLEEVELESS	LIGHT	HEAVY
SKIRT					LIGHT	HEAVY
SLACKS					LIGHT	HEAVY
OTHER:						

REFERENCE ENSEMBLE NO.† W41 I_{cl} 0.69

*Adjusted per Calibration Data.
†Refers to Ensembles Listed in Tables A3 and A4.

Appendix B

Thermal Insulating Values for Representative Men's and Woman's Ensembles

Table A3. Thermal Insulating Values for Representative Men's Ensembles Reproduced from Seppanen et al., [23].

TIV's for Representative Men's Ensembles

Ensemble No.	Under Shirt	Socks	Trousers	Shirt	Tie	Sweater	Jacket	f_{cl}	I_c [1,4]
15	[3]	Cool-1[2]	Cool-12	SS-Cool Knit 14				1.20	0.48
24		Cool-1	Cool-12	LS-Cool Knit 16				1.18	0.49
23		Cool-1	Jeans-11	SS-Woven 9				1.21	0.49
10		Cool-1	Cool-12	SS-Woven 9				1.21	0.51
16		Cool-1	Cool-12	SS-Warm Knit 15				1.17	0.52
14		Warm-2	Cool-12	SS-Woven 9				1.21	0.57
13	SS 5	Cool-1	Cool-12	SS-Woven 9				1.21	0.59
26		Cool-1	Warm-13	SS-Woven 9				1.23	0.61
12	SL 3	Cool-1	Cool-12	SS-Woven 9				1.21	0.62
17	SL 3	Cool-1	Cool-12	LS-Woven 10				1.22	0.65
25		Cool-1	Cool-12	LS-Warm Knit 17				1.24	0.76
21	SL 3	Cool-1	Cool-12	SS-Woven 9		LS-Cool 18		1.25	0.81
11		Cool-1	Cool-12	SS-Woven 9	Narrow 7		Cool 20	1.25	0.89
22	SL 3	Cool-1	Cool-12	SS-Woven 9		LS-Warm 19		1.25	0.90
18	SL 3	Cool-1	Cool-12	SS-Woven 9			Cool 20	1.25	0.92
19	SL 3	Cool-1	Cool-12	SS-Woven 9	Narrow 7		Cool 20	1.25	0.92
20	SL 3	Cool-1	Cool-12	SS-Woven 9	Narrow 7		Warm 21	1.26	0.92
27	SL 3	Cool-1	Warm-13	SS-Woven 9	Narrow 7		Warm 21	1.26	1.00

Two garments of each type were tested, one with low thermal resistance (cool) and one with higher thermal resistance (warm).

[1] *Average of 4 measurements, 2 at $\Delta t \simeq 10F$ and 2 at $\Delta t \simeq 20F$.*

[2] *Garment numbers correspond to those in Appendix A.*

[3] *SS = short sleeve LS = long sleeve SL = sleeveless*

[4] *All ensembles include cotton briefs and low quarter shoes.*

Table A4. Thermal Insulating Values for Representative Women's Ensembles Reproduced from Seppanen et al., [23].

TIV's for Representative Women's Ensembles

Ensemble No.	Dress	Skirt	Slacks	Blouse	Sweater	Jacket	Under[6] wear	f_{cl}	I_c[1,5]
45	SL[2,3] Cool-7						I	1.05	0.21
44	SL Cool-7						II	1.05	0.21
65	SL Cool-7			SS Cool-16			II	1.08	0.32
60		Cool-9		SS Cool-16			II	1.12	0.33
51		Cool-9		LS Cool-11			II	1.12	0.36
49		Cool-9			LS Cool-15		II	1.10	0.40
53		Cool-9		SS Cool-16	SL Cool-14		II	1.10	0.42
62		Cool-9		LS Cool-11		LS Cool-17	II	1.16	0.45
63		Cool-9		SS Cool-16		LS Cool-17	II	1.16	0.49
50		Warm-10		LS Warm-M10			II	1.12	0.51
57			Cool-12	SS Cool-16			II	1.20	0.51
56			Cool-12		LS Cool 15		II	1.16	0.58
59			Cool-12	SS Cool-16	SL Cool-14		II	1.15	0.58
47		Warm-10			LS Warm-M19		II	1.15	0.65
48		Warm-10			LS Warm-M19		I	1.15	0.65
46		Warm-10			LS Warm-M19		V	1.15	0.66
42	LS Warm-8						II	1.22	0.68
66		Warm-10			LS Warm-M19		VI	1.15	0.68
41	LS Warm-8						III	1.22	0.69
40	LS Warm-8						IV	1.22	0.71

Continued on next page

Table A4. Continued

TIV's for Representative Women's Ensembles

Ensemble No.	Dress	Skirt	Slacks	Blouse	Sweater	Jacket	Under[6] wear	f_{cl}	$I_c^{1,5}$
64	LS Warm-8			LS Warm-M10			II	1.22	0.73
61		Warm-10		LS Warm-M10		LS Warm-M20	II	1.20	0.80
52		Warm-10		LS Warm-M10	LS Warm-M19		II	1.12	0.80
56			Warm-13	LS Warm-M10			II	1.22	0.82
54			Warm-13		LS Warm-M19		II	1.24	0.89
58			Warm-13	LS Warm-M10	LS Warm-M19		II	1.24	1.09

Two garments of each type were tested, one with low thermal resistance (cool) and one with higher thermal resistance (warm).

[1]*Average of 4 measurements, 2 at $\Delta t \simeq 10$ F and 2 at $\Delta t \simeq 20$ F.*
[2]*SL = sleeveless SS = short sleeve LS = long sleeve*
[3]*Numbers of garments correspond to those in Appendix A.*
[4]*Garment numbers preceded by M are for men's garments used in women's ensemble.*
[5]*All ensembles include low quarter shoes.*
[6]*Underwear key.*

- I *cotton bra, acetate panties*
- II *cotton bra, acetate panties, nylon panti-hose*
- III *II plus full length nylon slip*
- IV *III plus elastic nylon-lycra girdle*
- V *II plus nylon half slip and elastic nylon-lycra girdle*
- VI *II plus knee socks*

Appendix C

Close-up Views of Environmental Testing Instrument Sensors

THIS BOOK CONTAINS SEVERAL DOCUMENTS THAT ARE OF POOR QUALITY DUE TO BEING A PHOTOCOPY OF A PHOTO.

THIS IS AS RECEIVED FROM CUSTOMER.

Figure A1. Close-up of Dry Bulb Temperature Sensor

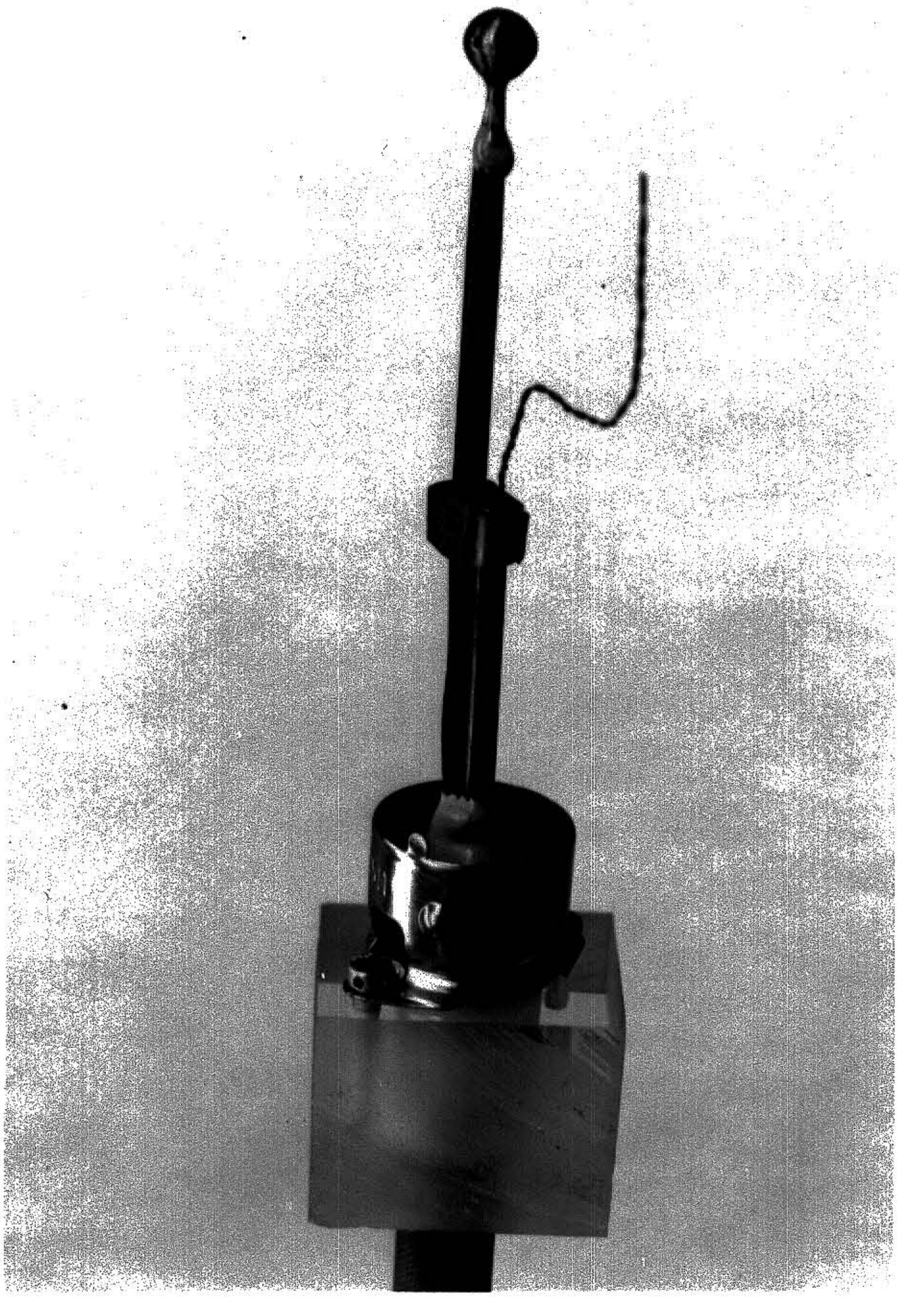


Figure A2. Close-up of Airspeed Sensor

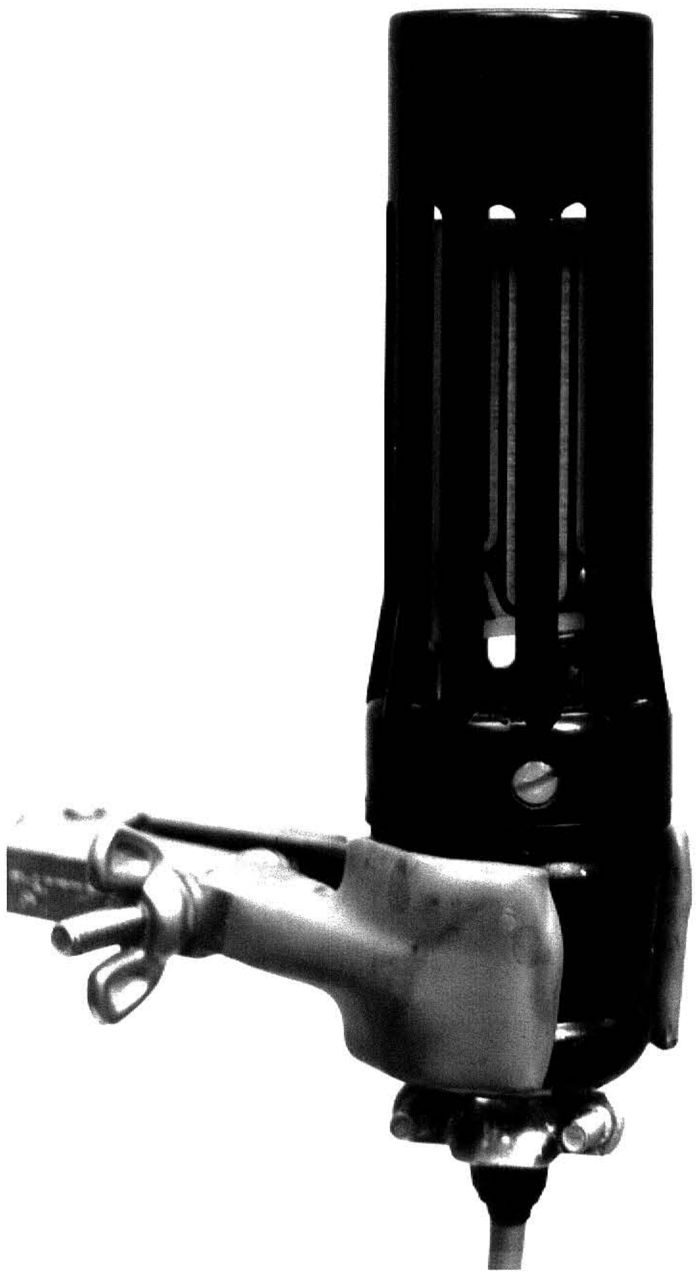


Figure A3. Close-up of Humidity Sensor

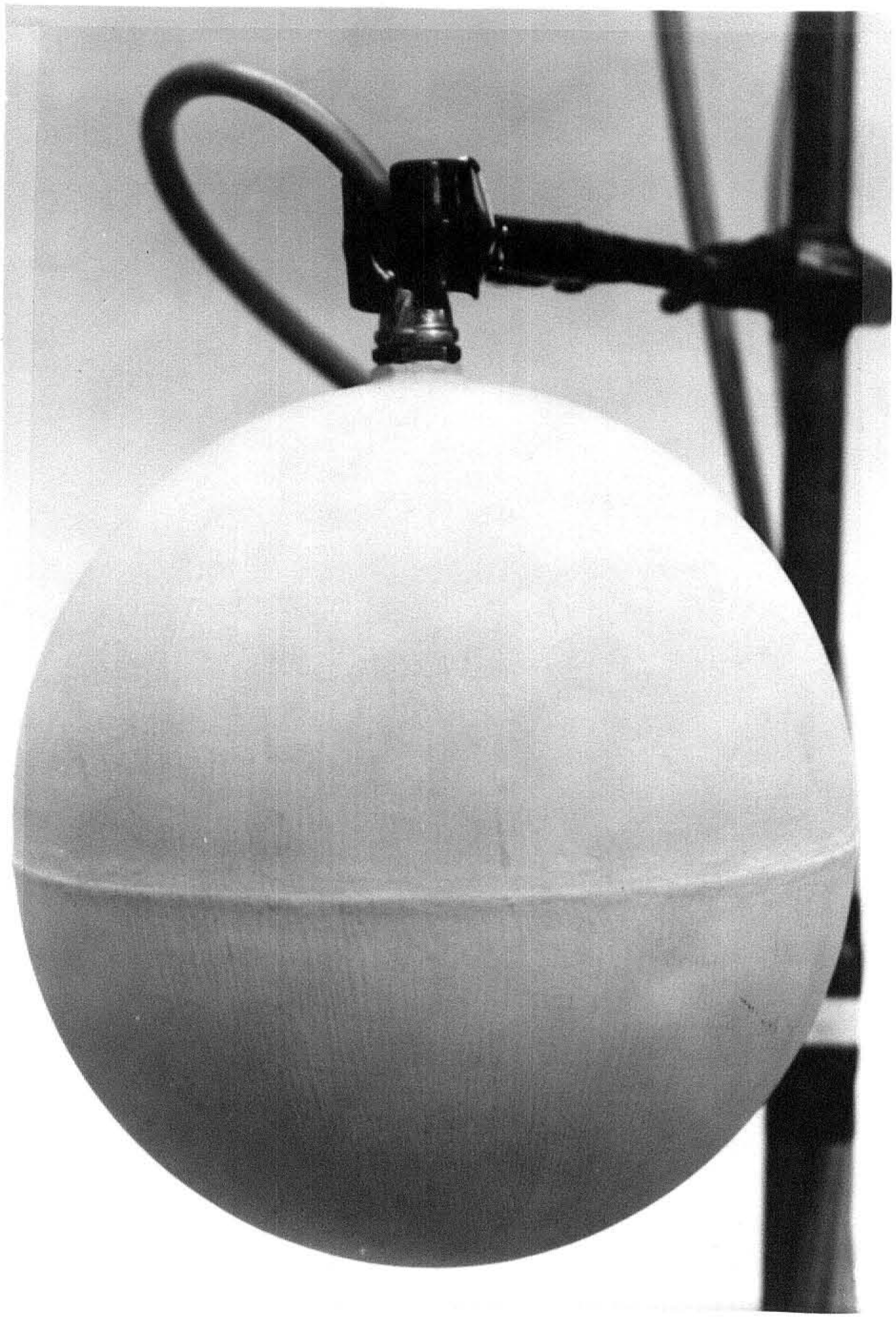


Figure A4. Close-up of Enclosure for Globe Temperature Sensor

Appendix D

Computer Program for Calculation of Environmental Variables

```
C     THIS PROGRAM CALCULATES MEAN RADIANT TEMPERATURE, ADJUSTED DRY
C     BULB TEMPERATURE, AND WATER VAPOR PRESSURE FROM THE MEASURED INPUT
C     VARIABLES OF DRY BULB TEMPERATURE, GLOBE TEMPERATURE, RELATIVE
C     HUMIDITY, AIRSPEED, AND SATURATED WATER VAPOR PRESSURE.
C     THE VARIABLE SYMBOLS AND THEIR UNITS ARE AS FOLLOWS-
C       TDB     DRY BULB TEMPERATURE, DEGREES FAHRENHEIT
C       TG      GLOBE TEMPERATURE, DEGREES FAHRENHEIT
C       RH      RELATIVE HUMIDITY, PER CENT
C       VEL     AIRSPEED, FEET PER MINUTE
C       PS      SATURATED WATER VAPOR PRESSURE, MILLIMETERS OF MERCURY
C       PA      PARTIAL VAPOR PRESSURE OF WATER, MILLIMETERS OF MERCURY
C       TMRT    MEAN RADIANT TEMPERATURE, DEGREES FAHRENHEIT
C       TADJDB  ADJUSTED DRY BULB TEMPERATURE , DEGREES FAHRENHEIT
      DIMENSION TDB(34),TG(34),VEL(34),RH(34)
      DIMENSION PS(34),PA(34),TMRT(34),TADJDB(34)
      DO 100 I=1,34
  100 READ(5,101) TDB(I),TG(I),VEL(I),RH(I),PS(I)
  101 FORMAT(5F16.5)
      DO 200 I=1,34
C     THIS IS EQUATION 1 FROM THE TEXT TO CALCULATE PARTIAL VAPOR
C     PRESSURE OF WATER
      PA(I)=RH(I)*PS(I)/100.0
C     THIS IS EQUATION 2 FROM THE TEXT TO CALCULATE MEAN RADIANT
C     TEMPERATURE
      TMRT(I)=((1.0+0.157*SQRT(VEL(I)))*(TG(I)-TDB(I)))+TDB(I)
C     THIS IS EQUATION 3 FROM THE TEXT TO CALCULATE ADJUSTED DRY BULB
C     TEMPERATURE
      TADJDB(I)=(TMRT(I)+TDB(I))/2.0
  200 CONTINUE
      WRITE(6,600)
  600 FORMAT('1')
      WRITE(6,601)
  601 FORMAT(12X,'DRY BULB',9X,'GLOBE',11X,'AIR',10X,'RELATIVE',6X,'SAT
     1VAPOR',5X,'PART VAPOR',3X,'MEAN RADIANT',3X,'ADJ DRY BULB')
      WRITE(6,602)
  602 FORMAT(2X,'SUBJECT',2X,'TEMPERATURE',4X,'TEMPERATURE',7X,'SPEED',9
     1X,'HUMIDITY',7X,'PRESSURE',6X,'PRESSURE',5X,'TEMPERATURE',4X,'TEMP
     1ERATURE',/)
      DO 603 I=1,34
  603 WRITE(6,604) I,TDB(I),TG(I),VEL(I),RH(I),PS(I),PA(I),TMRT(I)
     1,TADJDB(I)
  604 FORMAT(5X,I2,7X,4(F5.2,10X),F5.2,9X,F5.2,10X,F5.2,10X,F5.2,/)
      WRITE(6,600)
      STOP
      END
```

Appendix E

Tabulated Data

Table A5. Tabulation of Reduced Data

SUBJECT NUMBER	APT. NUM.	TIME	DATE	WINDOW EXP.	AGE	SEX	I_{cl} clo	REF.† ENSEMBLE	t_{db} °F	t_g °F	VEL FPM	*RH %	*t_{mrt} °F	t_{adjdb} °F	P_s mmHg	P_a mmHg	VOTE
1	3F	9:30A	9-24-74	WEST	86	M	0.65	M17	77.3	78.3	9.5	50.0	78.8	78.0	23.99	12.00	5
2	2F	3:00P	9-25-74	WEST	63	M	0.59	M13	76.2	76.5	15.8	52.9	76.7	76.4	23.13	12.24	5
3	11B	3:00P	9-27-74	EAST	75	M	0.51	M10	78.4	79.4	9.5	56.6	79.9	79.1	24.88	14.08	5
4	8G	11:00A	9-24-74	SOUTH	72	M	0.65	M17	78.0	79.4	9.5	46.9	80.1	79.0	24.55	11.51	5
5	12E	10:00A	9-26-74	WEST	70	F	0.36	W51	78.3	79.1	61.4	52.5	80.1	79.2	24.80	13.02	5
6	7E	4:30P	9-25-74	WEST	78	F	0.61	M26	77.7	78.3	21.8	45.3	78.7	78.2	24.31	11.01	5
7	7G	4:00P	9-25-74	SOUTH	71	F	0.48	M15	79.3	80.0	3.0	44.6	80.2	79.8	25.63	11.43	5
8	2F	3:00P	9-25-74	WEST	68	F	0.48	M15	76.2	76.5	15.8	52.9	76.7	76.4	23.13	12.24	5
9	4G	3:00P	9-23-74	SOUTH	63	F	0.48	M15	74.4	75.0	22.6	44.3	75.4	74.9	21.79	9.65	5
10	9A	10:30A	9-24-74	SOUTH	77	F	0.48	M15	76.0	76.7	8.5	46.6	77.0	76.5	22.98	10.71	5
11	9D	10:00A	9-24-74	NORTH	71	F	0.49	M24	75.2	76.0	7.0	49.4	76.3	75.8	22.38	11.06	6
12	9E	10:30A	9-23-74	WEST	73	F	0.49	M24	76.0	76.9	19.2	46.2	77.5	76.8	22.98	10.62	5
13	3C	9:30A	9-23-74	EAST	76	F	0.71	M40	77.4	77.9	8.5	49.4	78.1	77.8	24.07	11.89	4
14	11F	4:30P	9-23-74	WEST	69	F	0.59	M13	76.9	77.9	31.3	43.9	78.8	77.8	23.68	10.40	6

*Adjusted Values.
†Refers to Ensembles Listed in Tables A3 and A4.

Table A5. Continued

SUBJECT NUMBER	APT. NUM.	TIME	DATE	WINDOW EXP.	AGE	SEX	I_{cl} clo	REF.† ENSEMBLE	t_{db} °F	t_g °F	VEL FPM	*RH %	*t_{mrt} °F	t_{adjdb} °F	P_s mmHg	P_a mmHg	VOTE
15	7D	4:30P	9-27-74	NORTH	63	F	0.59	M13	77.5	78.2	3.0	57.2	78.4	77.9	24.15	13.81	5
16	8A	4:00P	9-23-74	SOUTH	78	F	0.65	W47	77.2	78.0	15.8	47.1	78.5	77.8	23.91	11.26	5
17	7F	3:30P	9-25-74	WEST	66	F	0.69	W41	76.4	76.9	6.0	51.7	77.1	76.7	23.29	12.04	5
18	4H	3:30P	9-24-74	EAST	63	F	0.65	W48	75.7	76.6	6.0	48.9	76.9	76.3	22.75	11.12	5
19	6D	3:30P	9-27-74	NORTH	77	F	0.21	W44	76.5	77.4	4.5	56.9	77.7	77.1	23.37	13.30	5
20	7H	4:00P	9-27-74	EAST	73	F	0.69	W41	78.8	79.9	6.0	58.8	80.3	79.6	25.21	14.82	5
21	3D	9:00A	9-23-74	NORTH	80	F	0.69	W41	74.1	74.9	6.0	51.5	75.2	74.6	21.57	11.11	5
22	12B	3:00P	9-26-74	WEST	62	F	0.61	M26	78.2	78.9	8.5	52.2	79.2	78.7	24.72	12.90	5
23	3G	10:00A	9-23-74	SOUTH	77	F	1.00	M27	76.6	77.5	4.5	48.3	77.8	77.2	23.45	11.33	5
24	10D	9:00A	9-26-74	NORTH	90	F	0.32	W65	74.8	75.5	7.0	56.0	75.8	75.3	22.08	12.36	4
25	5F	9:30A	9-25-74	WEST	84	F	0.32	W65	72.5	73.3	9.5	55.0	73.7	73.1	20.44	11.24	4
26	10H	9:30A	9-26-74	EAST	78	F	0.32	W65	80.5	81.2	7.0	52.4	81.5	81.0	26.65	13.96	6
27	2B	2:00P	9-26-74	EAST	80	F	0.32	W65	79.1	79.9	44.2	56.9	80.7	79.9	25.46	14.49	6
28	8C	3:30P	9-23-74	EAST	76	F	0.32	W65	77.0	78.0	39.0	48.0	79.0	78.0	23.76	11.40	5

*Adjusted Values.
†Refers to Ensembles Listed in Tables A3 and A4.

Table A5. Continued

SUBJECT NUMBER	APT. NUM.	TIME	DATE	WINDOW EXP.	AGE	SEX	I_{cl} clo	REF.† ENSEMBLE	t_{db} °F	t_g °F	VEL FPM	*RH %	*t_{mrt} °F	t_{adjdb} °F	P_s mmHg	P_a mmHg	VOTE
29	8D	4:00P	9-24-74	NORTH	82	F	0.32	W65	75.6	76.4	4.5	52.2	76.7	76.1	22.68	11.84	5
30	5G	9:00A	9-25-74	SOUTH	78	F	0.32	W65	73.2	74.1	7.0	53.0	74.5	73.8	20.93	11.09	5
31	11B	3:00P	9-27-74	EAST	73	F	0.32	W65	78.4	79.4	9.5	56.6	79.9	79.1	24.88	14.08	5
32	6B	9:00A	9-27-74	EAST	73	F	0.32	W65	77.0	78.1	15.8	56.9	78.8	77.9	23.76	13.52	5
33	2C	4:30P	9-26-74	EAST	82	F	0.32	W65	78.8	78.8	7.0	51.4	78.8	78.8	25.21	12.96	5
34	10F	3:30P	9-26-74	WEST	76	F	0.32	W65	79.8	80.1	7.0	51.7	80.2	80.0	26.05	13.47	5

*Adjusted Values.
†Refers to Ensembles Listed in Tables A3 and A4.

Appendix F

Uncertainty Analysis

UNCERTAINTY ANALYSIS

The findings reported in this study are the results of combining individually measured static quantities via some mathematical relationship. If the conclusions that were reached are to be of value, there must be some kind of statement dealing with the "goodness" or reliability of the measured quantities and computed values. The process by which this criteria is established is called the uncertainty analysis.

First, it is necessary to establish the uncertainty in the measured values of dry bulb temperature (t_{db}), globe temperature (t_g), airspeed (VEL) and relative humidity (RH).

The specifications for the identical thermistor circuits used in the measurement of dry bulb temperature and globe temperature quote an absolute accuracy of ± 0.27F. This may be taken to mean the odds are 20 to 1 that the output of the temperature circuits will fall inside of this limit. A second source of error is the ability or inability of the digital multimeter to accurately display the calculated results of the circuits. The specifications quote a maximum error for the digital multimeter of 0.05% of reading ± 1 digit. The resolution of the multimeter is 0.1 millivolt which corresponds to 0.1F. Therefore, when reading a typical temperature of 75.0F, the maximum error would be 0.14F. An accepted way of combining the error of the temperature circuit with the error in reading out the result would be to use the root-mean-squared value of the errors [26]. In other words:

$$\lambda_T = \sqrt{(0.14)^2 = (0.27)^2}$$

$$\lambda_T = 0.30F$$

where λ_T is the limit of error in the globe temperature and dry bulb temperature measurements. One can expect 95% of the dry bulb temperature and globe temperature measurements to be within 0.3F of correct.

The values for airspeed used in the computer program were first corrected per calibration data. This procedure eliminates the uncertainty in the ability of the airspeed circuit to calculate the correct value. However, there is still the uncertainty in the ability of the multimeter to indicate the correct value. For a typical airspeed of 9.0 FPM and a maximum error of 0.05% of reading $\pm$ 1 digit in the multimeter, the maximum error would be 0.1 FPM. So λ_{VEL} = 0.1 FPM means one might expect 95% of all the corrected airspeed readings to be within 0.1 FPM of correct.

As with airspeed measurements, the relative humidity figures were also corrected with calibration data. Therefore, with a typical measurement of 50.2% RH, one might expect 95% of all corrected values to be within 0.1% RH of correct, or λ_{RH} = 0.1% RH.

The manner in which these uncertainties propagate through the mathematical relationships of adjusted dry bulb temperature ($t_{adj\ db}$) and vapor pressure (P_a) are also important. By doing a sensitivity analysis, one can determine which individual uncertainties have the greatest influence on the calculated result.

The generalized sensitivity equation for a function of two variables, such as R = f(X,Y), is given by Sprague and Nash [26] as:

$$\frac{\lambda_R}{R} = \frac{\left[\frac{\partial f}{\partial X}\right] X}{f(X,Y)} \frac{\lambda_X}{X} + \frac{\left[\frac{\partial f}{\partial Y}\right] Y}{f(X,Y)} \frac{\lambda_Y}{Y} . \qquad \text{(1A)}$$

The quantities $\frac{\lambda_R}{R}$, $\frac{\lambda_X}{X}$ and $\frac{\lambda_Y}{Y}$ are known as the normalized uncertainties and are given the symbols μ_R, μ_X and μ_Y respectively. The quantities in brackets are called the sensitivity factors and are given the symbols S_X and S_Y. Now equation 1A may be written as:

$$\mu_R = S_X\mu_X + S_Y\mu_Y \ . \qquad (2A)$$

Although equation 2A indicates the relative significance of the uncertainties in the measured quantities, it is not actually used to calculate a numerical value for μ_R. To do this one uses a root-mean-squared error equation of the form:

$$\mu_R = \sqrt{S_X^2\mu_X^2 + S_Y^2\mu_Y^2} \ . \qquad (3A)$$

Recalling the equation for mean radiant temperature (t_{mrt}) in the text, the sensitivity equation for t_{mrt} may be written for a typical case. For the case where:

$$t_g = 76.0F$$
$$t_{db} = 75.0F$$
$$VEL = 9.0 \text{ FPM}$$
$$t_{mrt} = 76.5F,$$

the sensitivity equation is:

$$\mu_{t_{mrt}} = 0.003\mu_{VEL} + 1.462\mu_{t_g} - 0.462\mu_{t_{db}} \ .$$

This equation indicates that globe temperature has the greatest influence on mean radiant temperature while airspeed influences it the least. The numerical value for $\mu_{t_{mrt}}$ for the typical case mentioned previously is 0.006.

Using the same precedure as before with the same typical values, the sensitivity equation for adjusted dry bulb temperature ($t_{adj\ db}$) is:

$$\mu_{t_{adj\ db}} = 0.505\mu_{t_{mrt}} + 0.495\mu_{t_{db}} .$$

The numerical value for $\mu_{t_{adj\ db}}$ is 0.0036. Recalling the definition of the normalized uncertainty, the limit of error in adjusted dry bulb temperature can now be established. Since

$$\mu_{t_{adj\ db}} = \frac{\lambda_{t_{adj\ db}}}{t_{adj\ db}} ,$$

with an adjusted dry bulb temperature of 75.8F, the uncertainty, $\lambda_{t_{adj\ db}}$, is ± 0.27F.

The sensitivity equation for vapor pressure (Pa) is:

$$\mu_{P_a} = 1.0\mu_{P_s} + 1.0\mu_{RH} .$$

This means vapor pressure is equally sensitive to both relative humidity and saturated vapor pressure (P_s). Saturated vapor pressure was determined using a steam table to find the value of P_s for the corresponding dry bulb temperature. The ± 0.3F uncertainty in t_{db} means an uncertainty of ± 0.23 mm Hg in saturated vapor pressure. For a typical case where,

$$t_{db} = 75.2\text{F}$$

$$P_s = 22.38 \text{ mm Hg}$$

$$RH = 50.5\%$$

$$P_a = 11.23 \text{ mm Hg}$$

the numerical value for the normalized uncertainty in vapor pressure is 0.01. For the calculated value of P_a of 11.23 mm Hg, the limit of error, λ_{P_a}, is ± 0.11 mm Hg.

ACKNOWLEDGEMENTS

The author would like to express his sincere gratitude to his major advisor, Dr. R. O. Turnquist, for his encouragement and guidance throughout this study.

Appreciation is due my committee members, Dr. R. L. Gorton, Dr. J. G. Thompson and Dr. R. R. Gallagher for their recommendations and assistance.

Further thanks are extended to Dr. F. H. Rohles for his suggestion of the original topic and continued interest throughout the project.

The author also gratefully acknowledges the cooperation of 34 residents of the Apartment Tower in making this study possible.

A special thanks to my wife, Nancy, for typing the manuscript and for her economic and moral support throughout the project.

The financial support of the American Society of Heating, Refrigerating and Air-Conditioning Engineers is also gratefully acknowledged.

VITA

Roger Phillip Volmer

Candidate for the Degree of

Master of Science

Thesis: A STUDY OF THE THERMAL ENVIRONMENT IN APARTMENTS OF THE ELDERLY

Major Field: Mechanical Engineering

Biographical:

Personal Data: Born March 9, 1951 at Parsons, Kansas, the first child of Joseph Murrell and Mary Louise Volmer. Married to former Nancy Diane Letourneau, Wichita, Kansas.

Education: Graduated from St. Paul High School in May, 1969. Attended Wichita State University from September, 1969, to December, 1970, majoring in aeronautical engineering. Transferred to Kansas State University in January, 1971 and received B.S.M.E. in January, 1974. Completed course requirements for M.S. degree in mechanical engineering at Kansas State University in December, 1974.

Professional: Assisted with ASHRAE sponsored research programs to: determine clothing insulation values of typical indoor ensembles, spring and fall semesters 1971; help design and build Environmental Testing Instrument, fall semester 1973 and spring semester 1974. Student assistant for Thermodynamics I at Kansas State University, fall semester 1972. Lab instructor for Mechanical Engineering Lab I at Kansas State University, spring semester 1973. Worked as field engineer, summer 1972, for Martin K. Eby

VITA (continued)

Roger Phillip Volmer

Construction Company, Wichita, Kansas. Worked as Mechanical Engineer, summer 1973, in the Technical Services Group of Continental Oil Company's refinery in Ponca City, Oklahoma. Student member of ASHRAE, ASME. Member of Pi Tau Sigma, Tau Beta Pi, Phi Kappa Phi. Member of the Roman Catholic Church.

A STUDY OF THE THERMAL ENVIRONMENT IN APARTMENTS OF THE ELDERLY

by

ROGER PHILLIP VOLMER

B.S.M.E., Kansas State University, 1973

AN ABSTRACT OF A MASTER'S THESIS

submitted in partial fulfillment of the

requirements for the degree

MASTER OF SCIENCE

Department of Mechanical Engineering

KANSAS STATE UNIVERSITY

Manhattan, Kansas

1975

ABSTRACT

The Apartment Tower, a public housing project for senior citizens located in Manhattan, Kansas, was chosen as the test facility to sample thermal environmental conditions in apartments of the elderly and to determine their comfort response to those conditions. Designed especially for persons over 62, the Apartment Tower is a 12 story structure with 88 apartments.

Thirty-four residents (mean age of 74 years), participated by making their apartments available to be sampled and by casting a comfort vote describing their thermal sensation from conditions existing in their apartment at the time of the test session.

The environmental variables of dry bulb temperature, globe temperature, relative humidity and airspeed were measured with the Environmental Testing Instrument, a prototype instrument designed and built by Institute for Environmental Research engineers at Kansas State University. The values for adjusted dry bulb temperature and vapor pressure were calculated by a computer using the observed values of the four measured variables. Clothing insulation values were also determined for the ensembles worn during the testing sessions.

Comfort responses included feelings of slightly warm, neutral and slightly cool. The 27 conditions receiving neutral votes yielded an average of 77.6F for adjusted dry bulb temperature. The 77.6F line was then constructed on the New ASHRAE Comfort Chart. This line was shown to bisect the KSU-ASHRAE Comfort Envelope, an envelope developed with college student data. This finding supports the now generally accepted fact that thermal comfort is relatively unaffected by age.

The average clothing insulation value for the ensembles worn by the subjects was 0.49 clo. This contrasts with the 0.5 clo to 1.0 clo specification of ASHRAE Standard 55-74 and the recommended 0.6 clo to 0.8 clo for the KSU-ASHRAE Comfort Envelope suggesting that perhaps people are wearing lighter clothing about their residences than was expected.