HEAT PRODUCTION OF COLLEGE-AGE PERSONS AT FOUR LEVELS OF ACTIVITY AND THEIR CORRESPONDING THERMAL COMFORT CONDITIONS

by 149

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INTRODUCTION

Man is continuously striving to create a more comfortable and convenient environment. Human energy expenditure and thermal comfort are directly related to the environment, and, consequently, they have been the subjects of much research; yet the subjects are so complex and sometimes nebulous that the termination of these efforts is not in sight.

In previous studies under ASHRAE sponsorship at the Institute for Environmental Research at Kansas State University, Manhattan, Kansas, Nevins et al. (87) and McNall et al. (81) reported the thermal comfort (thermally neutral) conditions for college-age men and women at four levels of activity: sedentary, low, medium and high. The primary purpose of this research was to determine the heat production (metabolic rates) of healthy college-age men and women at these levels of activity, to provide an easy method of predicting these values, to determine the effect of the environment on metabolic rate and to construct a proposed thermal comfort zone as a function of metabolic rate for college-age males and females. McNall et al. (81) predicted that the metabolic rates for the low, medium, and high activity levels would be approximately 600, 800 and 1000 Btu/hr for the average male subject and the conclusions of these authors regarding thermal comfort were based on these values. This thesis verifies the accuracy of their predictions. The results of this study indicate that the average metabolic rates for the three hour test period at the four levels of activity were 391, 631, 835 and 1057 Btu/hr for the men and 303, 485, 656 and 823 Btu/hr for the women. The results of the sedentary tests reported here also indicated that the metabolic rate was independent of the environmental temperature over a range of 66 to 78 F.

McNall _et al_. (81) reported that the thermally neutral conditions for the low, medium and high levels of activity were 72, 66, and 60 F dry bulb respectively, all at relative humdidities between 25 and 65%. Nevins _et al_. (87) reported that, for sedentary activity, the comfort conditions ranged from 77 to 79 F dry bulb for corresponding relative humidities of 70 to 30%. Both previous studies indicate that men and women performing the same activity preferred similar thermally neutral conditions but that women are more sensitive to small changes in the thermal environment than are men.

LITERATURE REVIEW

A. Lavoisier (1743-1794) was the first to discover the importance of oxygen gas and to describe the principles of combustion both within and outside the human body. Studies by J. Von Liebigs, published in 1843, showed that carbohydrates, fats, and protein are burned within the body, and V. Regnault and J. Reiset in 1849 demonstrated that the respiratory quotient depended upon the nature of the foodstuffs being oxidized and not upon the species of animal. W. O. Atwater (1844-1907) constructed the first human respiration calorimeter at Middletown, Connecticut---a major breakthrough in the field of human energy metabolism (95). In the early part of the 20th century, F. G. Benedict carried on many studies regarding the energy expenditure of man and various species of animals at the Nutrition Laboratory of the Carnegie Institute of Washington at Boston, Massachusetts (1) (8). Since that time, the measurement of the human energy expenditure of various activities has increased considerably.

Passmore and Durnin (89) reported that the validity of using rates of oxygen consumption as the basis for measuring energy has been firmly established, and the literature contains many reports using this method (8) (26) (31). Furthermore, the use of indirect, closed-circuit calorimetry in measuring the oxygen consumption rate has also been validated (8). Using these methods, studies have been conducted to determine the human energy expenditure of men and women in a multitude of activities. Many of these studies have been conducted in altered environments to determine the environmental effects on other physiological responses as well. Passmore and Durnin (89), Karpovich (64), and the <u>Bioastronautics Data Book</u> (102)

have made substantial progress in summarizing the vast amount of literature available on human energy expenditure for various exercises. In these references, one can find information on a large number of common everyday activities as well as some that are not so common. However, one is sometimes confused by the large variations in the energy metabolism reported by various authors for a given activity. The reasons for these variations are nearly as numerous as the number of studies conducted. Variations in people, conditions, methods and equipment are the primary causes. However, one cannot overlook the fact that errors are sometimes reported. The "state-of-the-art" of human energy metabolism has progressed since Atwater and Benedict's initial studies, but the inherent problems of leaks, "auspumpung" (the "washing-out" of carbon dioxide in the lungs) and errors in gas analysis still occur today.

Quite often, metabolic rates are normalized for unit body surface area. This practice evolved from the surface law theory. Kleiber (68) classified the theories for the interpretation of the surface law of animal metabolism as follows:

> The metabolic rate of animals must be proportioned to their body surface:
>
> 1. because the rate of heat transfer between an animal and the environment is proportional to the animal's body surface area.
> 2. because the intensity of the flow of nutrients (in particular, of oxidizable material and oxygen) is a function of the sum of internal surfaces which in turn is proportional to the body surface.
> 3. because the rate of supply of oxidizable material and oxygen to the tissues is a function of the mean intensity of the blood

flow, which is proportional to the cross-sectional area of the blood vessels, which is, in turn, proportional to the area of body surface.

4. because the chemical composition of the animals is a function of body size.
5. because the anatomical composition of animals is a function of body size.
6. because the inherited metabolic requirement of tissues is a function of body size.

Kleiber went on to state that the heat transfer theory is the most convincing and that there may be some merit to the hemodynamics aspect. However, the remaining four have no evidence in their favor.

Human thermal comfort studies were first begun during the early 1900's. The American Society of Heating, and Ventilating Engineers (later the American Society of Heating, Refrigerating and Air Conditioning Engineers) pioneered this field. During the period 1913 - 1923, Professor John Sheppard at Teachers Normal College, Chicago, Illinois, introduced the term "Comfort Zone" (51) (87). In 1923, Houghton and Yaglou (51, 52) published their findings; their findings established "Lines of Equal Comfort," defined "Effective Temperature," and determined the "Comfort Zone". In these experiments, the subjects walked from one room, controlled with respect to temperature and humidity, to another room that had a different temperature and humidity condition. The conditions of the second room were adjusted until the immediate reaction of the subjects gave identical comfort sensations or "Equal Warmth."

These results were then plotted on a dry bulb-wet bulb diagram and were known first as lines of equal warmth. The effective temperature was defined as "An Arbitrary Index", because it combines into a single value, the effects of dry bulb temperature, humidity, and air motion on the perception of apparent warmth or cold of the human body. The comfort zone was defined as including those effective temperatures over which 50% of the people were comfortable. On this basis, for clothed, sedentary subjects of both sexes, Houghton and Yaglou (51) found the zone limits to be 62 and 69 F ET with a comfort line at 64 F ET. The comfort line would be at 68 F dry bulb temperature for a 45% relative humidity.

Extension of the original studies was undertaken to determine the effect of air motion and clothing on comfort sensations. In 1929, a revised comfort chart showing the effect of summer climate on the comfort zone resulted from the work of Yaglou and Drinker (114). The summer zone was found to be between 64 and 79 F ET. and the comfort line was 71 F ET (e.g. 76 F - 50%). This zone included all votes indicating that a state of comfort existed, rather than 50% or more of the votes as used in the Houghton and Yaglou (51) study. Since that time, continued studies have been conducted on thermal comfort and human heat exchange. Some of those who have contributed are Bedford (7), Fahnestock *et al*. (30, 31, 32), Gagge (35), Hardy and DuBois (42), Houghton *et al.* (49, 54, 55), Inouye *et al*. (59, 60), Leopold (73), McNall and Sutton (82), and Winslow *et al*. (107, 108, 109, 110, 111). This list is by no means complete but is representative of part of the research conducted in these areas. The most recent works on the comfort zone have been described by Koch *et al*. (70), Nevins (85), Nevins *et al*. (86, 87) and McNall *et al*. (81). The research reported in these pages was designed to augment the work of Nevins _et al_. (87) and McNall _et al_. (81), who reported the thermal comfort (thermally neutral) conditions for four levels of activity.

One of the reasons for the large amount of research in the area of thermal comfort stemmed from the fact that comfort is an extremely nebulous variable (86). The concept of comfort is purely subjective (72). It is the product of interplay between physiological, biological, sociological and psychological elements.

Rohles (91), Gagge (35), and Hickish (49) listed some of the factors which must be considered when conducting environmental research regarding human thermal comfort, and Rohles classified many of them into three groups as follows:

PHYSICAL

1. Temperature
2. Humidity
3. Force Field
4. Air Movement
5. Atmospheric Pressure
6. Inspired Gas
7. Radiation
8. Area-Volume
9. Light
10. Sound
11. Color
12. Smell
13. Touch

ORGANISTIC

1. Age
2. Diet
3. Rhythmicity
4. BMR
5. Sex

RECIPROCATIVE

1. Activity
2. Clothing
3. Exposure Time
4. Social
5. Health

There were problems and faults with the English language in defining thermal comfort in terms of a verbal scale (35). The problem of defining criteria for comfort was further complicated by the daily variations in an individual's reaction to an environment and by variations among individuals. The problems encountered have led to the numerous discussions and definitions of comfort. ASHRAE Standard 55-66 (100) Thermal Comfort Conditions defined thermal comfort as "that condition of mind which expresses satisfaction with the thermal environment." The standard also states that "The dry bulb temperature shall be between 73 and 77F at any point within the occupied zone, at any time, when MRT [mean radiant temperature] is approximately equal to the dry bulb temperature." Also "The relative humidity shall not exceed 60 percent of any point in the occupied zone. For many reasons other than for thermal comfort, the relative humidity shall not fall below 20 percent."

Leopold (73) defined comfort as "The absence of discomfort or annoyance due to temperature and atmospheric effect indoors," and discussed comfort and design criteria from an economical and practical standpoint as well. He stated that subjects participating in a test on thermal comfort are inclined to report their sensations the way they think they feel and that, since individuals differ with regard to physiology, work, rest habits, and food and drink habits, there can be no condition which is optimum for all people at all times. However, as activity increases, the workers become less aware of the thermal environment and of minor changes in the thermal environment. McNall et al. (81) found that men become less sensitive to dry bulb temperature changes as the level of activity increased. The female data were less conclusive and, at the high activity level of 823 Btu/hr as determined in this research, the females exhibited an unexpected extreme sensitivity to temperature and humidity changes. The authors suggested the possibility that fatigue was the cause of this finding. Nevins (85) stated that the criteria for thermal comfort are "specifications for the indoor environment in which an arbitrary percentage of the occupants will express thermal comfort."

Carrier (22) stated that the range of satisfactory and practical humidities was between 35% and 65%, the latter represented a maximum summer condition and the former a minimum winter condition. Miura (83) found that a difference of 50 percent in relative humidity was evidently perceptible for seated and clothed normal persons at dry bulb temperatures between 70 and 80 F. His results indicated that the relative humidity exerted a smaller effect upon the senses of comfort than Yaglou's thermometric chart indicated, unless the relative humidity was changed suddenly. Fahnestock and Werden (32) stated that indoor temperatures in the range of 73 to 77 F with relative humidities between 25 and 60% are reasonable and comfortable the year (around) in any latitude in the United States. For sedentary or slightly active people in a dry bulb temperature range of 73 to 78 F, a range of relative humidities of 25 to 70% produces a negligible effect on their comfort and well-being, but, as temperature increases above 78 F, humidity effects become very important; because evaporation becomes the main avenue of heat loss (86). Increased metabolism produces a similar effect.

Hickish (49) defined the upper limit of the comfort zone in terms of temperatures at which more than 20% of the people questioned experienced thermal discomfort. Further, Hickish (49) stated that there is evidence that, even though there is a personal freedom in the choice of clothing, men and women factory workers in light occupations do not require different thermal conditions. Inouye (59) also reported that the presence of men and women in the same space does not require alterations in accepted specifications for its air conditioning. This is interesting in that the results of this research and the literature showed that the heat production for a given activity is less for women than for men. However, women adjust for this by having a smaller evaporative heat loss.

Man is a homeotherm who constantly adjusts his internal temperature to environmental fluctuations (72). The hypothalmus may be considered the chief center for integration of the body's temperature control. However, other parts of the body, for instance the spinal cord, may have an influence on the hypothalmus or may provide a secondary type of regulation (27).

When a nude, resting man is exposed to a range of still air temperatures from 81-86 F, his body needs to take no particular action to maintain its heat balance (1). This is termed the neutral zone, and, if the person is clothed or active the temperature range will naturally be lower. When he strays from the neutral range, his body makes adjustments. For mild exposure to cold, there is a zone immediately below the neutral zone called the zone of vasomotor regulation against cold. Within this zone, blood vessels adjacent to the skin constrict and, thus, restrict the flow of blood and consequently of heat to the surface of the skin. For still colder environments, the restriction of blood flow is not sufficient to provide adequate protection. This range of conditions is called the zone of metabolic regulation against cold. Spontaneous increases in activity and shivering result in an increase in heat production and, therefore, prevent the deep body temperature from falling. Beyond this range, the body enters the zone of inevitable body cooling, where disastrous results may occur.

On the warm side of the neutral zone, there exists, first, a zone of vasomotor regulation against heat. This zone corresponds to that against cold. In this zone, the blood vessels dilate, and increased blood flow with increased transport of heat to the skin surface results. Beyond this zone lies the zone of evaporative regulation against heat where the body reacts through the operation of the sweat glands for evaporative cooling. When evaporative cooling is insufficient, the body enters the zone of inevitable body heating. Thermal comfort exists when the body is in the zone of vaso-motor regulation or the neutral zone (86). Man's body is like a heat engine in the thermodynamic sense in that it continually transforms the chemical energy of food into mechanical work and heat and is subject to the Law of the Conservation of

Energy (20). However, it is unlike a heat engine in that all repairs are made while the body is in operation (95). The principal end products of the oxidation of food are carbon dioxide, water, and heat. Heat loss from the body is dependent on two separate systems. The most important system is composed of the physical factors of the surrounding environment and the other system is composed of are the physiological factors which operate entirely within the body. The physiological factors control the flow of heat from the interior body core to the exterior surface of the skin and regulate evaporative heat loss. The physical factors operate from the skin to the environment.

In order for the human body to maintain thermal neutrality, it is essential that the body maintain a rather close balance between heat production (metabolism) and heat loss (32). This heat interchange can be expressed as follows:

$$M = \pm C_d \pm C_v \pm R \pm E_v \pm S \pm W \tag{1}$$

where:

M = Rate of metabolic heat production within the body (always positive).

C_d = Rate of conductive heat loss (+) or gain (-) from the body

C_v = Rate of convective heat loss (+) or gain (-) from the body

R = Rate of radiative heat loss (+) or gain (-) from the body

E_v = Rate of evaporative heat loss (+) or gain (-) from the body

S = Rate of heat storage within the body as manifested by an increase in body temperature

W = External mechanical work done by the body on its surroundings..

Heat loss from the body is considered positive as indicated by the equation. Under normal thermally neutral conditions, C_d is usually negligible, C_v, R, and E_v are positive, S is zero and W may or may not be a factor. This analysis will be based on a clothed body in air. C_d could become an influencing factor if a substantial portion of the body was in contact with a cold or hot surface, for instance, immersed in cold water. If the medium in which the body is in contact is lower than the mean clothing temperature, C_d is positive, if higher than the mean clothing temperature, C_d is negative. C_d can be expressed from elementary heat transfer as follows (62):

$$C_d = K\ A\ \frac{dt}{dx} \tag{2}$$

where: K = Thermal conductivity coefficient of the external medium

A = Area of contact between the subject and the external medium

$\frac{dt}{dx}$ = Gradient of temperature in the external medium in the outward direction from the subject

Convective heat loss, C_v occurs when the temperature of the air is less than that of the clothing. Convective heat loss can be expressed by the following equation (33):

$$C_v = A_{Du} \cdot f_{cl} \cdot h_c\ (t_{cl} - t_a) \tag{3}$$

where: A_{Du} = The nude surface area of the body

f_{cl} = Ratio of the surface area of the clothed body to the nude body

h_c = Convective heat transfer coefficient

t_{cl} = Mean temperature of the exterior surface of the clothing

t_a = Air temperature

The magnitude of the h_c is dependent on the velocity of the air and on the temperature difference $t_{cl} - t_a$, and methods of its computation can be found in the literature (33) (108).

Radiative heat loss occurs when the mean radiant temperature (MRT) is less than the mean clothing temperature. Radiative heat gain occurs when the opposite is true. Radiative heat loss can be expressed as follows: (62)

$$R = \frac{f_{eff} \cdot f_{cl} \cdot A_{Du} \cdot \sigma \, (T_{cl}^4 - T_{MRT}^4)}{\frac{1}{\varepsilon_{cl}} + \frac{A_{Du} \cdot f_{eff} \cdot f_{cl}}{A_{enc}} \left[\frac{1}{\varepsilon_{enc}} - 1 \right]} \qquad \text{-}4\text{-}$$

where:

f_{eff} = The ratio of the effective radiation area of the clothed body to the surface area of the clothed body

σ = The Stefan-Boltzmann radiation constant

T_{MRT} = Absolute mean radiant temperature

ε_{cl} = Emissivity of the outer surface of the clothed body

A_{enc} = Area of the enclosure

ε_{enc} = Emissivity of the enclosure

If the ratio, $\frac{A_{Du} \cdot f_{eff} \cdot f_{cl}}{A_{enc}}$, is relatively small, as it normally is, equation -4- reduces to:

$$R = f_{eff} \cdot f_{cl} \cdot A_{Du} \cdot \sigma \cdot \varepsilon_{cl} \, (T_{cl}^4 - T_{MRT}^4). \qquad \text{-}5\text{-}$$

Guibert and Taylor (37) reported that f_{eff} when the subject is erect is 0.77 and 0.70, when seated, while the ratio of the clothed projected area to the nude projected area = f_{cl} is 1.14 ± 0.06.

Heat loss by evaporation is insensible when no perspiration is visibly apparent and the person does not have a sensation of sweating. Sensible evaporation occurs when sweat is visible on the skin and the person has a sensation of sweating.

Hardy (43) reported that sweat is more than 99% water. Therefore, the amount of heat lost when sweat is evaporated is equal to the latent heat of evaporation of water at the temperature of the skin. Man at rest in a cool or neutral environment loses approximately 24% of his metabolic heat by evaporation of the insensible perspiration. About half of this water is lost through the respiratory passages and half through the skin. This loss of heat is not physiologically controlled but rather the result of transudation through the skin. Even under carefully controlled conditions, there is considerable variation in the percent of heat loss by insensible perspiration (19-30%) due to individual differences.

Under high humidity conditions, the body increases the blood supply to the skin, and this results in increased sweat secretion. Therefore, the body is able to maintain evaporative heat loss at the desired level (109).

The phenomenon of evaporative heat loss can be broken up into three parts: Latent respiratory heat loss, water vapor diffusion through the skin, and sweat secretion. Latent respiratory heat loss occurs from the transfer of water vapor to the inspired air. When air is inspired, water vapor from the mucosal lining in the respiratory tract is transferred to the air.
As the air proceeds downward into the alveoli the temperature of the air is

very close to the core temperature of the body and is saturated with water vapor. Convective heat transfer to the inspired air also occurs simultaneously, however, it is a small (normally 2% or less) portion of the total heat loss. Upon exhalation, a small amount of the convective and evaporative heat absorbed are transferred back to the body.

Fanger (33) has reported that latent respiratory heat loss is a function of the pulmonary ventilation rate and the difference in humidity ratios of the inspired and expired air or:

$$R_w = V\,(W_{ex} - W_a)\,r \qquad (6)$$

where: R_w = Latent respiration heat loss (Btu/hr)

V = Pulmonary ventilation (lb/hr) = $0.01320 \cdot M$

where: M = Metabolic rate (Btu/hr)

W_{ex} = Humidity ratio of the expired air (lb water vapor/lb dry air)

W_a = Humidity ratio of inspired air (lb/water vapor/lb dry air)

r = Heat of vaporization of water at 95 F

The water vapor diffusion component produces some confusion. Some observers report that the process is always positive and/or purely a diffusional process (39) (33) (47) (38). Others report that at pressure gradients below 21 mm to 23 mm Hg diffusion does not occur and in fact the skin may absorb water (18) (19) (103). Some type of diffusion process would appear reasonable to the engineer and Fanger (33) offered the following equation based on data by Inouye et al. (60).

$$D = 0.35 \cdot A_{Du} (P_s - P_a) \qquad \{7\}$$

where:

D = Water vapor diffusion (Kcal/hr)

A_{Du} = DuBois Body Area (m^2)

P_s = Saturated water vapor pressure at the skin temperature (mm Hg)

P_a = Partial pressure of water vapor in the surrounding air (mm Hg)

The heat loss by sweat secretion is more difficult to define and express mathematically since it is physiologically controlled. However, data has been taken on this variable, at the Institute for Environmental Research, with college-age males and females performing the same activities reported in this paper, in an environment found to be thermally neutral by McNall _et al._ (81). The results indicate that the total evaporative heat loss (latent respiration, diffusion, and sweat secretion) is a function of the metabolic rate and the body surface area. The linear regression equation established for both males and females is:

$$\overline{E}/A_{Du} = 0.512 \cdot M/A_{Du} - 11.7 \qquad \{8\}$$

where: $\overline{E}/A_{Du}$ = Mean total evaporative heat loss per unit body surface area (Kcal/m^2/hr)

M/A_{Du} = Metabolic rate per unit of body surface area (Kcal/m^2/hr)

The human body is a very intricate and unique entity. It is presently impossible for one to understand all of the processes and variables involved in heat production, heat loss and thermal comfort of the human body. However, by measuring the metabolic heat production at four levels of activity and correlating these results with the results of McNall _et al._ (81) and Nevins _et al._ (87), it was anticipated that a better understanding of these factors would result.

MATERIALS AND METHODS

Experimental Design

Since these experiments were designed to supplement and refine the results of Nevins et al. (87) and McNall et al. (81), the same four levels of activity used previously were employed in the investigation. It was believed that increments of approximately 200 Btu/hr would permit interpolation of the thermal comfort conditions for metabolic rates lying between those measured in this study. The number of subjects tested at each temperature and activity level with corresponding examples of activities from everyday life are given in Table 1; in addition, the expected metabolic rates at these activities are presented (1) (33) (102) (105).

The results of the sedentary studies showing the effect of the environment on the metabolic rates were applied to designing the thermal conditions for the low, medium and high activity levels. The results of this sedentary study showed that the thermal environment did not have a significant effect on metabolic rates over the range of 66-78F. Therefore, for simplicity, the low, medium and high activity studies were performed in an environment of 45% RH and a dry bulb temperature corresponding to that found to be thermally neutral for that particular level of activity by McNall et al. (81). In addition, the thermally neutral conditions permitted a more meaningful heat loss analysis as well as correlation with the results of McNall et al. (81).

The method of measuring the metabolic rates during the sedentary tests and the walking and standing periods of the low, medium and high activity tests permitted the determination of the particular energy costs of sitting quietly at rest, standing, and walking over the steps.

Table 1

Subjects, Temperature, Activity Level, Expected Metabolic Rates, and Corresponding Activities and Occupations of this Study.

Number of Subjects	Temperature-Humidity	Experimental Activity	Expected Metabolic Rates (Btu/hr)		Activities and Occupations
			Males	Females	
20	66/50	Sedentary-sitting quietly	375-425	290-340	Sitting at rest, reading, writing.
20	72/50	Sedentary-sitting quietly	375-425	290-340	
20	78/50	Sedentary-sitting quietly	375-425	290-340	
20*	72/45	Low; Walk 5 min/Stand 25 min	600-650	475-525	Light ironing, slow movement about a room, driving car in traffic, typing rapidly.
	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, heavy 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.

In regard to metabolic rates with sedentary and standing subjects, the data in the literature are often normalized for unit of body surface area (Btu/hr/ft^2), and metabolic rates for walking on a grade or climbing are often normalized for a unit clothed body weight (Btu/hr/lb). However, the construction of normal standards with these normalizations has been the subject of some discussion. Tanner (96) reported that, in physiology and clinical medicine, oxygen consumption is commonly expressed as per-weight or per-surface area ratios and that normal standards have been constructed on this basis. He believed that such standards are "theoretically fallacious and in practice, ..., misleading."

Kleiber (66) discussed the limitations of Tanner's statement and showed that reasoning power should not stop with the formulation of an empirical regression analysis. Furthermore, he reported that, in general, "ratios of equidimensional terms furnish the simplest and most general expressions for physiological relations. Other ratios are, however, also justified and may be best suited for particular problems."

A regression analysis was designed to correlate the metabolic rates of the various activities, evaporative heat loss, and the combined convective and radiative heat loss with the individuals' height and weight. Thus, was possible to determine just how well the normalizations mentioned fit the data and how they might be modified in future work to yield more accurate results. Also, it will be possible to conduct future tests of this nature and have a means of estimating the variables simply by measuring the individuals' height and weight.

The statistical models were:

$V = a_1(wt)^{b_1}$ (Model I)

$V = a_2(ht)^{b_2}$ (Model II)

$V = a_3(wt)^{b_3}(ht)^{b_4}$ (Model III)

where: V = Variable to be analyzed (metabolic rate, evaporative heat loss, or the combined convective and radiative heat loss.) (Btu/hr)

a = Regression coefficient determined from the analysis.

wt = Individual's nude weight for all variables except for the metabolic rate while walking where the clothed weight was used. (lb)

ht = Individual's height. (in)

b = Exponents determined from the regression analyses to which the weight and/or height are raised.

Test Subjects

For the sedentary studies, 30 males and 30 females were used as subjects. All were healthy volunteers from the Kansas State University student population and each received $5.00 for his participation. No subject was allowed to participate more than once during this sedentary study. The subjects were exposed to the thermal conditions for three hours in groups of five of one sex.

For the activity studies, 10 males and 10 females were used. Again all the subjects were healthy volunteers from the Kansas State University student population and each received $15.00 for his participation. The subjects participated in all three levels of activity. It was decided to use the same subjects for all three activities as a more uniform record of the metabolic rate is obtained, once the subject has become accustomed to the mouth-piece, breathing valve, and medical oxygen. Previous experience indicated that ten subjects of each sex should be adequate to allow meaningful statistical analysis. A physical description of the male and female subjects is given in Table 2. DuBois' formula was used in determining body surface areas (26).

Table 2

Physical Characteristics of the Test Subjects

Sex	No. of Subjs.	Activity	Height (in)	(Nude) Wt. (lb)	Body Surface Area (DuBois) (ft^2)	Age (yr)
Male	30	Sedentary	69.5±2.4	159.2±22.8	20.30±1.60	20.9±2.0
Female	30	Sedentary	64.8±2.2	129.0±20.6	17.65±1.50	19.8±1.7
Male	10	Low, Med. & High	68.9±2.6	160.6±27.1	20.22±1.49	21.0±2.1
Female	10	Low, Med. & High	64.5±2.7	131.9±22.8	17.76±1.68	19.6±1.7

Clothing

The standard clothing ensemble used in previous work at the Institute for Environmental research was used in this study (81) (87). Clothing was worn in the work of Nevins et al. (87) and McNall et al. (81), because their work was intended to furnish design criteria for men and women working in a temperate climate where clothing is worn both winter and summer. Therefore, although clothing presents an additional variable which must be considered, clothed subjects were used in this study. To minimize variation due to clothing, all subjects were clothed in cotton twill shirts and trousers with the shirts worn outside the trousers. In addition, male subjects wore cotton undershorts or jockey shorts but no undershirts or T-shirts, and female subjects wore brassieres and underpants. All subjects wore woolen socks without shoes. It was felt that this type and weight of clothing was typical of that normally worn by male persons working at or near the activity levels investigated. The insulative value of this clothing was recently re-evaluated, and the new value was 0.59 clo. This value was used instead of the previously reported value of 0.52 clo (81) (87). The male subject shown in Figures 1 and 2 is wearing the standard clothing ensemble.

Facilities and Apparatus

This research project was carried out at the Institute for Environmental Research, a division of the Department of Mechanical Engineering at Kansas State University, Manhattan, Kansas. This facility was financed jointly from funds provided by the Kansas Legislature and a matching grant from the Health Research Facilities Branch of the National Institute of Health, Department of Health, Education and Welfare.

The Institute housed the KSU-ASHRAE Environmental Test Chamber which was a gift from the American Society of Heating, Refrigerating and Air Conditioning Engineers (ASHRAE). The facility was originally located at the ASHRAE Laboratory at Cleveland, Ohio and was moved to Kansas State University and placed in operation in November, 1963. The tests were performed in this environmental chamber which is 12 feet wide, 24 feet long, and a ceiling height which is adjustable from 8 feet to 11 feet. During these tests, the height was 8 feet. A floor plan of the chamber and adjoining facilities is shown in Figure 3.

The illumination level measured at 30 inches above the floor with a GE light meter varied from 100 to 175 foot candles with an average of 133 foot candles. The background noise level averaged 69 db with all the equipment operating and no subjects in the room. A General Radio Co. Octave Band Noise Analyzer was used for the measurement. The air velocity averaged 30 fpm and

Figure 1. Measuring the sedentary metabolic rate of a male subject.

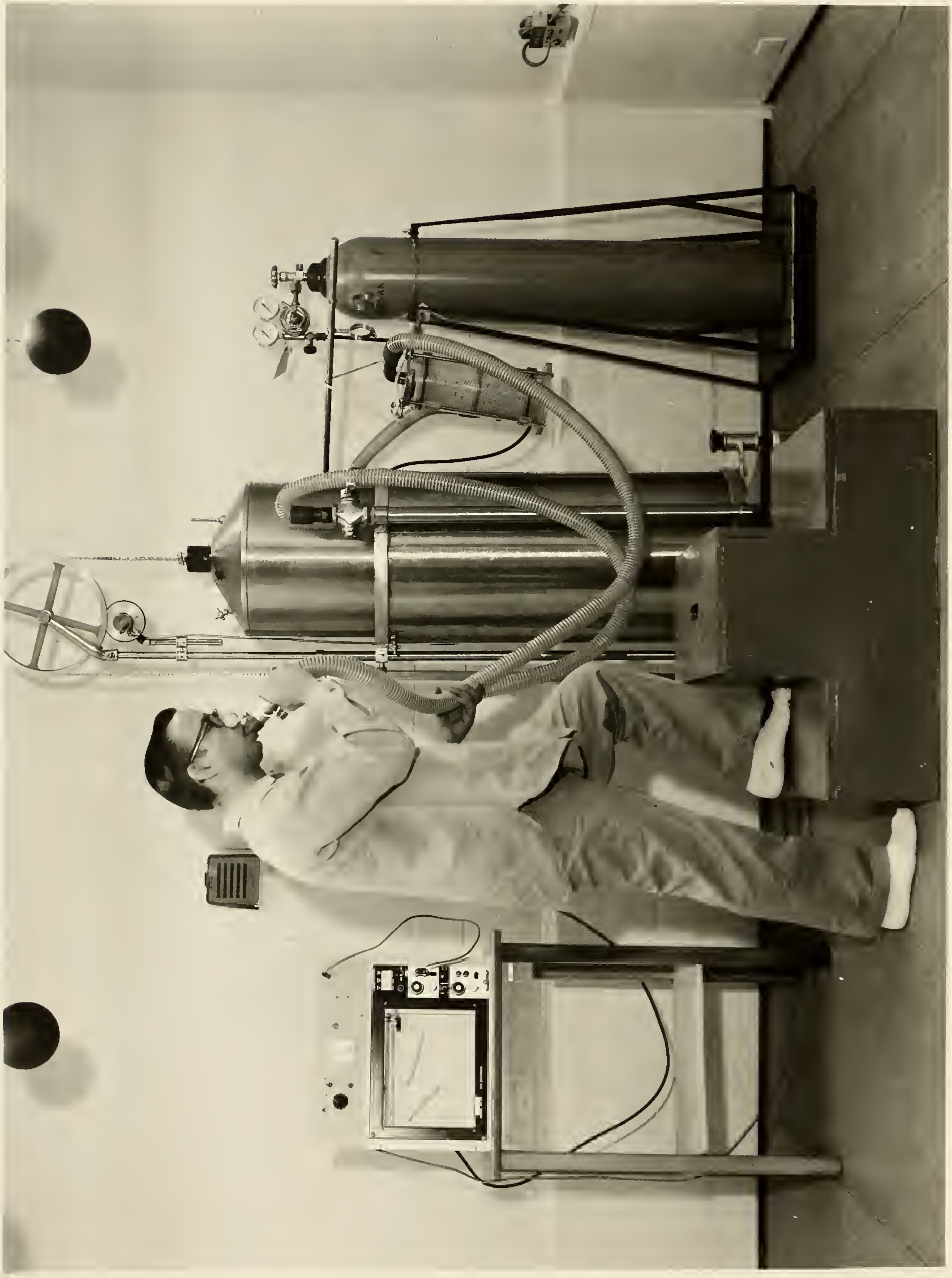

Figure 2. Measuring the metabolic rate of a male subject during the 5-minute walk period.

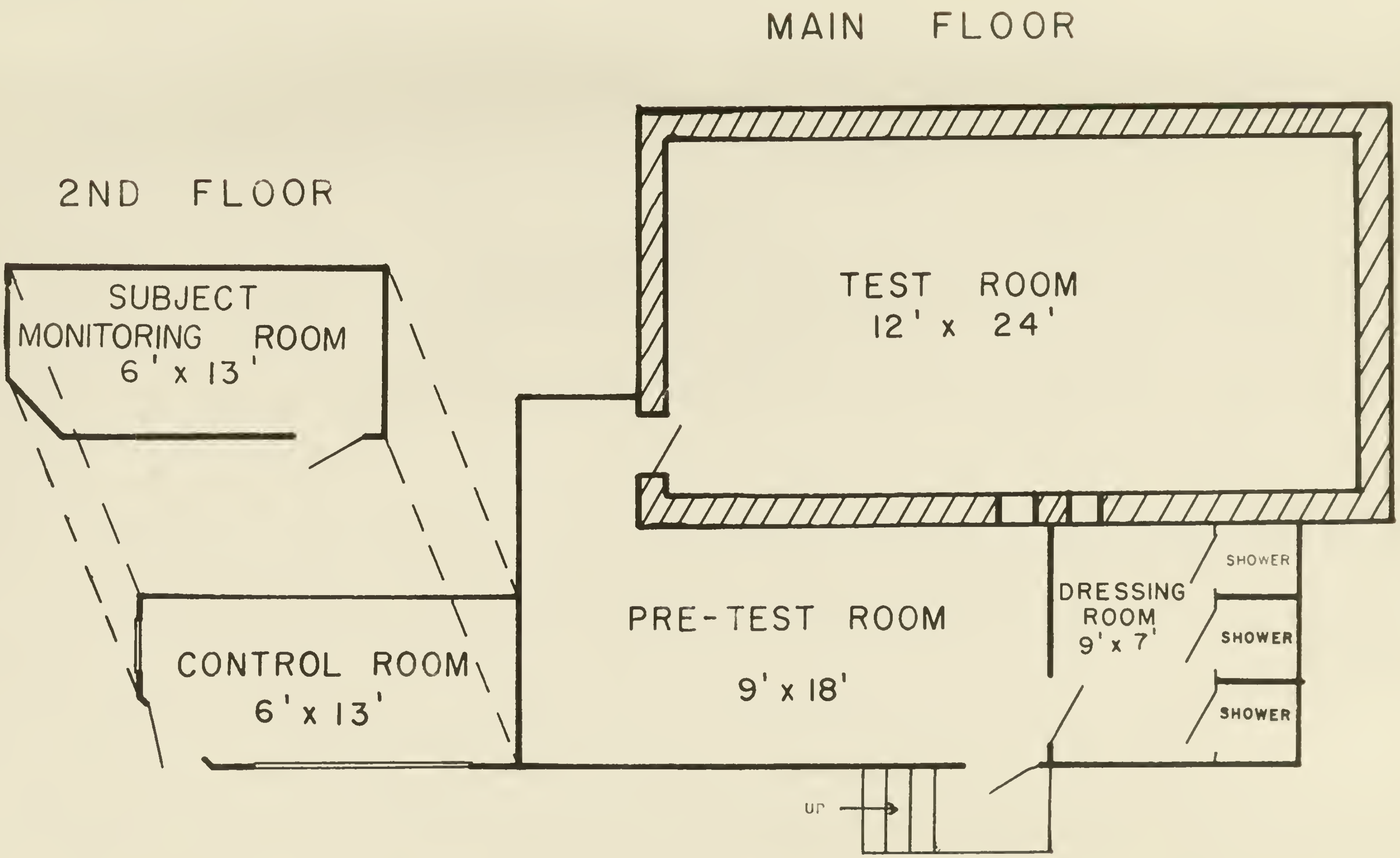

Figure 3. Floor plan of the KSU-ASHRAE environmental facilities.

varied from 25 to 35 fpm as measured by an Anemotherm Air Meter. Analysis of the increase in air motion over the subjects while walking over the steps was performed and the results indicate that the average velocities were: low activity 45 fpm, medium activity 54 fpm, and high activity 66 fpm. This analysis is reported in Appendix C. Throughout the tests, wall temperature was maintained equal to the air temperature.

The room was equipped with folding chairs and a table for the sedentary tests. For the activity tests, a set of two 9-inch steps were used for the walk portion of the tests as shown in Figure 2. A timer-buzzer (1 "click per second") was used to pace the walk of one step per second over the steps. During the stand portion of the tests the subjects read, studied or talked at a 40-inch high table.

All interior surfaces were aluminum to which copper tubes were attached on the back. These copper tubes carried heated and/or chilled water to control the surface temperature. The liquid circuits were arranged to provide four independent circuits: one for the floor, one for the ceiling, and two for the walls. This provided flexibility in maintaining different surface temperatures to simulate various conditions which could foreseeably be the subject of research investigations.

The system was designed so that air and surface temperatures from 40 to 150 F and relative humidity between 10% and 95% could be maintained through the system of a capillary washer, a sorbent dehumidifier, separate heating and cooling coils, fans, and ducting. Conditioned air entered through perforated inlet strips located between the ceiling panels and exited through a continuous slot at the floor around the perimeter of the room. It was possible to provide up to 50 air changes per hour.

A 15 hp refrigerating compressor supplied a 300 gallon insulated chilled liquid supply tank. The chilled liquid was circulated through the tank and heat exchanger by a pump which also provided adequate mixing in the tank. The temperature of the liquid in the tank was controlled by a pneumatic thermostat. A 220 gallon hot liquid storage tank was provided and maintained with steam supplied by the University's boilers. Utilizing a system of pneumatically controlled mixing valves and thermocouples, liquid with the desired temperature could be circulated through the panels of the four independent circuits.

The entire system was remotely and automatically controlled from the control room adjacent to the pre-test room. Electronic and pneumatic control equipment were used to maintain the predetermined conditions. The dry and wet bulb temperatures in the test room were measured by a motorized psychrometer and electronically fed back to the controllers in order to minimize temperature variations and cycling effects. An indicating potentiometer and a multipoint recorder were provided to measure wall surface temperatures, air temperatures, and globe temperatures. The globe temperature was obtained by thermocouples centered in the globe. Heat meters were attached to each panel and their output could be read on these instruments. Two graphic control panels were provided, one for the air circuit and one for the liquid circuits. Lights indicated those parts of the system which were in operation. Air or liquid temperatures at various locations in the system could be monitored. A physiological monitoring room was located above the control room. Instrumentation for measuring skin temperature, rectal temperature, and heart rate was available. Operant conditioning and programming equipment were also located in this room and were used to actuate and control the timer-buzzer.

A more detailed description of the construction, design, piping circuits, electronic controls, the original Cleveland arrangement, etc., are available from Tasker et al. (97) and Jennings and Givoni (63). A description of the present facility was included in the recent paper by Nevins et al. (87).

Metabolic rates were determined by indirect calorimetry. The oxygen consumption rate was measured in a closed-circuit system filled with medical oxygen and employing a carbon dioxide absorber. For the sedentary tests a Sanborn "Metabulator" was used (see Figure 1).

For the activity studies a larger oxygen capacity was required so a modified system was designed. This system, shown in Figure 2, consisted of a chain-compensated 120 liter water-sealed gasometer, a linear output potentiometer, a power supply, a large carbon dioxide cannister filled with indicating soda-lime, a pressurized tank of medical oxygen, and oxygen regulator, a two-way breathing valve, and the necessary hoses, mouthpiece, stands and electrical hook-up. The hoses were 1-1/8 inch reinforced plastic and were attached to a two-way high-capacity breathing valve and mouthpiece and the large, high-capacity carbon dioxide absorbent cannister. This provided a free-flowing, low resistance system which is mandatory to obtain an accurate metabolic cost of an activity without an undue increase caused by extra breathing labor due to restrictions.

A linear potentiometer rode on the pulley of the gasometer. This potentiometer is connected electrically through the power supply to the X-Y recorder. As the subject inhales and exhales, the potentiometer rotates causing an accompanying vertical movement on the recorder. The horizontal axis of the X-Y recorder is driven by a timer. With the time drive adjusted so that a full horizontal sweep of the recorder was approximately fifteen minutes, it was possible to measure the metabolic rate during the five minute walk and as much as ten minutes of the standing period following the walk. The gain on the vertical axis was adjusted so that the oxygen consumed during the five minute walk period would drop the position of the recorder pen approximately 3/4 of the height of the graph paper for the average size subject. By this means an easily defined steady state slope was obtained (See Figure 4).

A direct reading scale attached to the chain of the gasometer allowed for calibration of the relationship between the amount of oxygen consumed and the corresponding vertical displacement on the X-Y recorder. Time drive calibrations were performed before and after the test periods. The results were standardized to Standard Temperature, Pressure, and Dry Conditions (STPD).

Procedure

The sedentary subjects were randomly assigned to one of three temperature conditions, and, for the low, medium and high activity levels, the subjects were randomly assigned to an order of presentation of the activity levels employed. Morning tests were avoided since the previous work of Nevins et al. (87) indicated their results were significantly different from afternoon and evening tests. McNall et al. (81) suggested this might be due

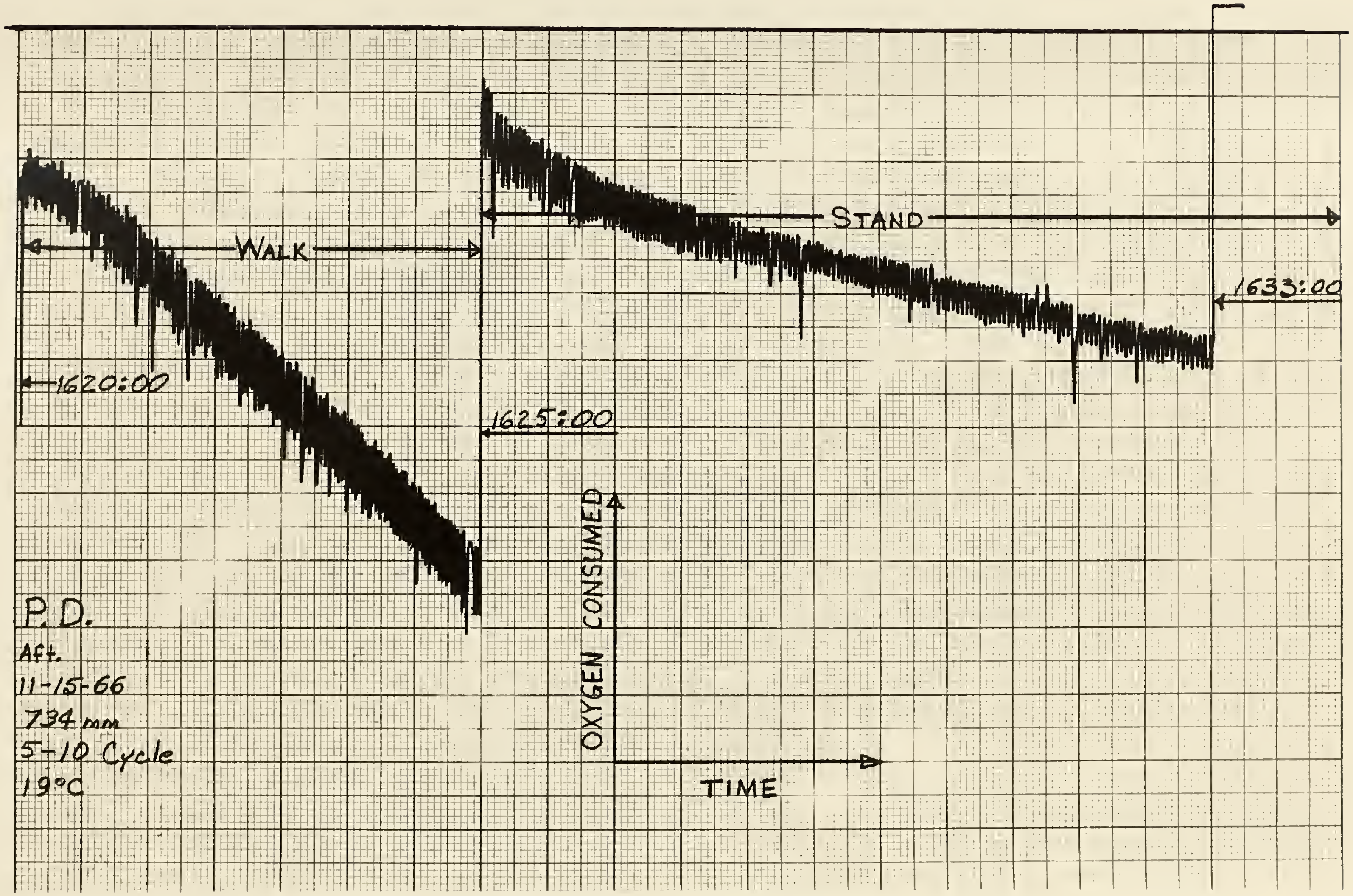

Figure 4. Typical record of the oxygen consumption rate of a female subject during the third hour walk and stand periods at the medium activity level.

to the effect of diurnal metabolic cycles. The afternoon tests were begun at 1:00 p.m. and the evening tests at 6:00 p.m. The sedentary study was conducted during January, 1966. A preliminary study of the low, medium and high activity levels was performed during February and March, 1966, and the results reported herein were conducted during November and early December, 1966.

The subjects reported for the tests and dressed in the standardized clothing. They then entered the pre-test room where their height, weight, heart rate, oral temperature and age were recorded by a registered nurse on record sheets. A sample of this record sheet is shown in Figure D-1. Nude weight was determined by subtracting the weight of a typical uniform from the clothed weight of the subjects. The criteria had been established to permit no subject to participate whose oral temperature was greater than 99 F. This situation, however, did not occur. The subjects were given an oral indoctrination regarding the purpose and method of the study. These indoctrinations are included in Appendices A and B. For the activity studies each subject was given a "Flow Sheet" to follow. A sample of this flow sheet is given in Figure D-2. The subjects entered the test room one at a time every ten minutes for the sedentary tests and every twenty minutes for the low, medium and high activity tests. This schedule was necessary so that each subject could be measured on one apparatus after identical exposure time in the test chamber. Upon entering the test room the subjects sat down at a table for the sedentary test. In the low, medium, and high activity the subjects began walking over the steps provided at the proper cadence of one step per second. In addition, one second was allowed for the subject to turn around at the bottom of the steps before beginning the walk back over the steps. During the first hour the subjects were permitted to familiarize themselves with the mouthpiece, breathing valve and nose clips.

For the low, medium, and high activity levels the subjects performed each of the three activities on different days; in groups of three of each sex except for one group where a married couple took part together. The same stand-walk cycles; walk five minutes - stand 25 minutes for the low activity level; walk five minutes - stand ten minutes for the medium activity level; walk five minutes - stand five minutes for the high activity level as reported by McNall et al. (81) were utilized. These cycles continued for the three hour exposure. A physical description of the step test is similar to that described for the Master two-step test (76). Because of the staggered entering intervals the heart rate of each subject could be taken at the half hour point of each hour. The nurse measured the heart rate immediately prior to and immediately after the walk period. No thermal sensation votes were taken since the use and annoyance of the metabolic equipment might influence the subjects' feeling of comfort. Furthermore, the large number (1140) of subjects used in determining the comfort conditions reported by Nevins et al. (87) and McNall et al. (81) was felt adequate to establish thermal comfort.

In both the sedentary and activity studies, the subjects' metabolic rates were measured at the end of each hour (see Figures 1 and 2). In the sedentary study, the metabolic rate was measured for an eight minute period, and, in the activity studies, it was measured while walking over the steps and while standing immediately after the walk for a total of 15 minutes.

The subjects were allowed to drink as much water as desired with each subject's consumption being recorded in the low, medium, and high activity tests. No food was consumed during the tests, and the subjects remained in the test chamber until the test period was completed. While in the test chamber, the subjects were permitted to read, study or quietly converse. Studying was permitted, because most observers indicate that mental effort has no positive influence on metabolic activity (89). At the end of their third hour, the subjects were removed from the test environment. In the activity studies, the post-test-weights, remaining drinking water and pulse rates were measured for each subject. The subjects were then free to dress and leave.

RESULTS

The primary purpose of this study was to make an accurate determination of metabolic rates of college-age males and females engaged in the same activities as those reported by Nevins et al. (87) and McNall et al. (81). The present results were correlated with the thermal comfort conditions reported in the two previous papers and are shown in Figure 5 (Proposed thermal comfort zone as a function of metabolic rate for average college-age males and females). In addition, the effect of environmental temperature on metabolic rate; the hourly variations in metabolic rate and heart rate; the effect of the level of activity on heart rate, metabolic rate, and evaporative heat loss; and the correlation of metabolic rate and evaporative heat loss with the subjects' height and weight were to be determined.

The mean metabolic rates and standard deviations for the sedentary tests are shown in Table 3. The mean physiological data and standard deviations for the high, medium and low activities are shown in Table 4. The mean hourly changes in sedentary metabolic rate are shown in Table 5 and the mean hourly changes in heart rate and metabolic rate for the high, medium and low levels of activity are shown in Table 6. The results of the analysis of variance for the sedentary studies are shown in Table 7 and the results for the high, medium and low levels of activity are shown in Table 8. The results of the regression analysis and supportive statistics used in predicting metabolic rate are shown in Table 9 and those used for predicting evaporative heat loss are shown in Table 10. The mean heart rate values for each activity level are shown in Figures 6 and 7. The 5% probability level was established as the minimum criteria for statistical significance for all of the analyses

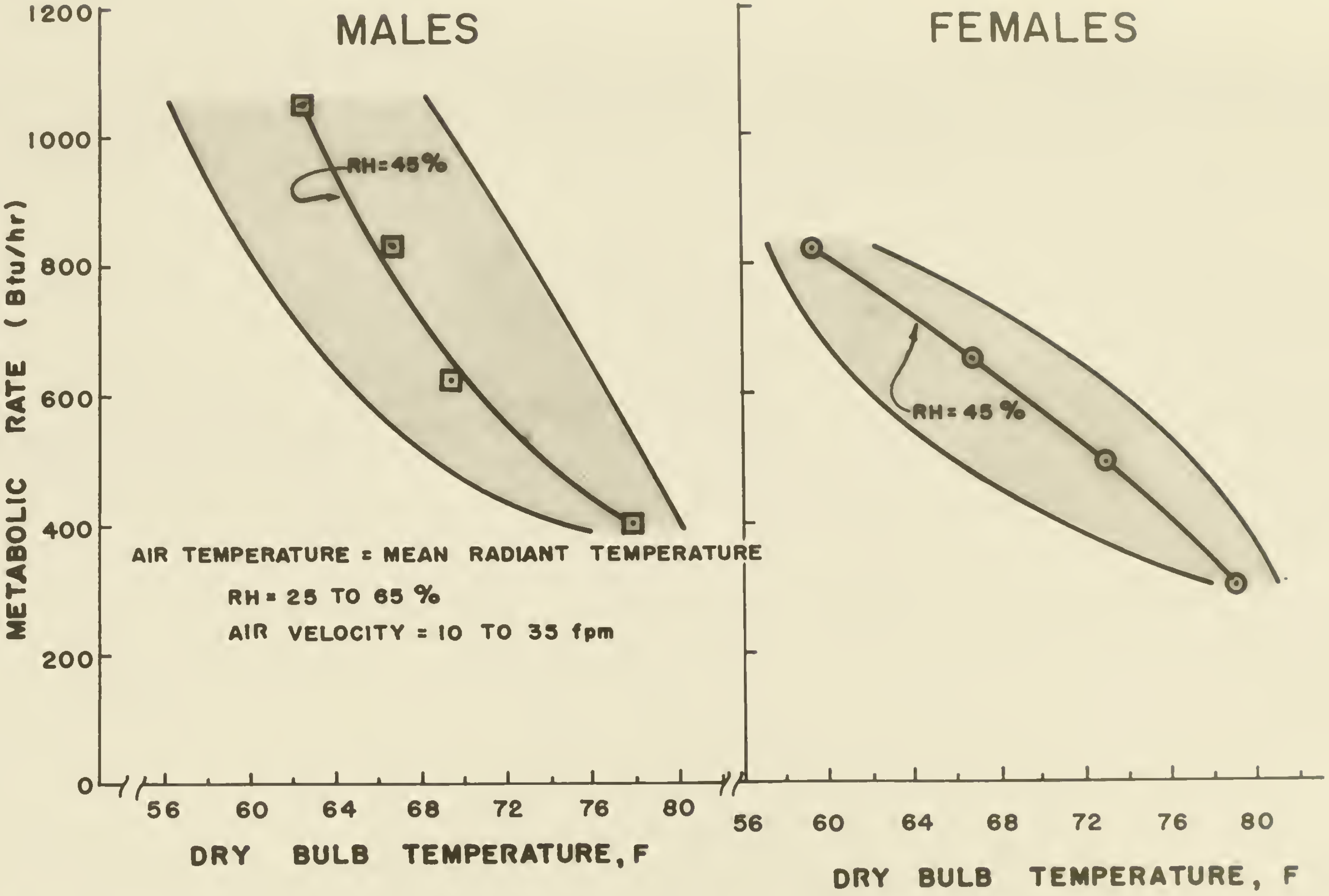

Figure 5. Proposed thermal comfort zone as a function of metabolic rate for average college-age males and females.

TABLE 3

Mean Metabolic Rates and Standard Deviations for Ten Male and Ten Female Subjects Engaged in Sedentary Activity at Each of Three Environmental Temperatures

I Metabolic Rate (Btu/hr)

	1st Hour		2nd Hour		3rd Hour	
Temp.	Males	Females	Males	Females	Males	Females
66	391±49	303±54	400±49	296±41	384±35	301±50
72	402±39	298±34	383±56	285±34	383±37	289±21
78	394±30	321±61	380±30	325±70	402±35	312±53
Grand Mean[#]	395±39	307±51	388±48	302±52	389±36	301±43

II Metabolic Rate (Btu/hr/ft^2)

	1st Hour		2nd Hour		3rd Hour	
Temp.	Males	Females	Males	Females	Males	Females
66	19.8±2.1	17.9±2.8	20.3±2.8	17.4±1.7	19.5±2.2	17.7±2.3
72	19.6±1.7	17.0±2.3	18.7±3.0	16.2±1.5	18.6±1.7	16.5±1.6
78	19.2±1.5	17.3±2.5	18.5±1.4	17.6±3.1	19.6±1.6	16.9±2.1
Grand Mean[#]	19.5±1.8	17.4±2.4	19.2±2.5	17.1±2.2	19.2±1.8	17.0±2.0

III Metabolic Rate Three Hour Average

	(Btu/hr)		(Btu/hr/ft^2)	
Temp.	Males	Females	Males	Females
66	391±45	300±47	19.9±2.9	17.1±2.3
72	389±44	291±29	19.0±2.1	16.6±1.7
78	392±31	319±61	17.3±1.5	17.3±2.6
Grand Mean[#]	391±39	303±43	19.3±2.1	17.2±2.2

[#] Grand Mean = The combined average of all three temperatures.

Table 4

Mean Physiological Data and Standard Deviations for Ten Female and Ten Male Subjects at the High, Medium and Low Levels of Activity

I Metabolic Rate While Walking (Btu/hr)

Activity	1st Hour		2nd Hour		3rd Hour	
Level	Males	Females	Males	Females	Males	Females
High	1658±248	1301±214	1651±244	1270±193	1641±232	1289±196
Medium	1649±288	1338±225	1601±254	1295±240	1586±258	1283±222
Low	1633±305	1265±217	1582±274	1266±224	1570±249	1258±208
Grand Mean#	1647±271	1301±213	1611±250	1277±213	1599±240	1277±192

II Metabolic Rate While Walking (Btu/hr/lb)

Activity	1st Hour		2nd Hour		3rd Hour	
Level	Males	Females	Males	Females	Males	Females
High	10.26±0.95	9.70±0.89	10.22±0.93	9.49±0.68	10.17±0.92	9.62±0.42
Medium	10.17±1.04	10.06±0.83	9.89±0.90	9.72±0.86	9.78±0.81	9.64±0.86
Low	10.06±0.68	9.49±0.57	9.78±0.85	9.49±0.58	9.71±0.72	9.45±0.74
Grand Mean#	10.17±0.91	9.75±0.79	9.96±0.90	9.56±0.71	9.89±0.82	9.57±0.68

III Metabolic Rate While Standing (Btu/hr)

Activity	1st Hour		2nd Hour		3rd Hour	
Level	Males	Females	Males	Females	Males	Females
High	445±65	353±36	467±50	358±44	480±53	362±41
Medium	449±54	328±32	440±49	328±34	451±65	339±29
Low	448±50	319±40	433±42	329±23	432±42	339±30

Table 4 Continued

IV Metabolic Rate While Standing (Btu/hr/ft^2)

Activity Level	1st Hour Males	Females	2nd Hour Males	Females	3rd Hour Males	Females
High	22.0±2.6	20.0±2.2	23.1±1.6	20.2±2.6	23.7±1.2	20.3±1.5
Medium	22.2±2.0	18.5±0.9	21.7±1.7	18.5±1.5	22.3±2.3	19.1±1.1
Low	22.2±1.9	18.0±1.8	21.5±1.4	18.7±1.8	21.4±1.6	19.2±1.5

V Average Metabolic Rate (Btu/hr)

Activity Level	1st Hour Males	Females	2nd Hour Males	Females	3rd Hour Males	Females
High	1052±142	827±121	1059±143	814±106	1061±140	826±114
Medium	849±128	665±92	827±114	650±99	829±124	653±91
Low	646±86	477±63	625±73	486±51	622±72	492±58

VI Combined Average Metabolic Rate (Btu/hr)

Activity Level	Average of 2nd & 3rd hrs. Males	Females	Average of 1st, 2nd & 3rd hrs. Males	Females
High	1060±142	820±110	1057±141	823±114
Medium	828±119	652±95	835±121	656±94
Low	623±73	489±54	631±77	485±57

VII Evaporative Heat Loss for the Three Hour Test Period

Activity Level	(Btu/hr) Males	Females	(Btu/hr/ft^2) Males	Females	% Evap. Loss of Heat Prod. Males	Females
High	462±257	368±124	22.6±7.1	20.3±5.5	42.8±10.6	43.8±10.3
Medium	373±142	262±110	18.2±5.9	15.0±4.8	43.7±11.1	40.4±11.6
Low	294±111	197±72	14.4±4.5	11.0±3.6	45.7±11.8	40.0±12.0
				Grand Mean#	44.1±10.9	41.4±11.1

Table 4 Concluded

VIII Heart Rate Pre-Test and Post Test (bpm)

Activity	Pre-Test		Post-Test		(Post-Test) - (Pre-Test)	
Level	Males	Females	Males	Females	Males	Females
High	80.2±7.9	92.4±16.3	86.0±14.0	94.4±9.3	5.8	2.0
Medium	78.6±11.2	84.4±12.3	80.8±11.6	91.8±13.0	2.2	7.4
Low	83.4±9.0	88.6±11.5	81.6±13.0	94.4±10.0	-1.8	3.8
Grand Mean#	80.7±9.4	88.4±13.5	82.8±12.7	93.5±10.6	2.1	5.1

IX Heart Rate Immediately Prior to a Walk (bpm)

Activity	1st Hour		2nd Hour		3rd Hour	
Level	Males	Females	Males	Females	Males	Females
High	85.6±10.4	100.4±10.2	80.8±8.8	94.4±13.0	81.6±14.7	96.0±8.8
Medium	84.6±7.9	94.6±12.4	83.2±9.8	94.2±11.9	81.6±9.7	96.2±11.7
Low	81.0±10.9	93.2±11.9	84.8±20.8	94.0±10.7	81.6±11.5	89.2±8.6
Grand Mean#	83.7±9.5	96.1±11.9	82.9±13.8	94.2±10.0	81.6±10.4	93.8±10.1

X Heart Rate Immediately After a Walk (bpm)

Activity	1st Hour		2nd Hour		3rd Hour	
Level	Males	Females	Males	Females	Males	Females
High	103.4±15.9	124.0±11.2	101.6±13.0	115.6±10.8	104.4±11.2	111.6±12.5
Medium	105.2±9.7	121.8±13.4	105.0±13.6	123.2±21.6	102.6±14.4	118.2±14.1
Low	104.4±13.0	114.2±13.4	103.8±19.8	121.4±7.7	100.0±13.7	119.2±11.9
Grand Mean#	104.3±13.2	120.0±13.0	103.4±17.5	120.1±14.5	102.3±12.8	116.3±13.1

Grand Mean = Combined average of all activity levels where appropriate.

TABLE 5

Mean Hourly Changes in Sedentary Metabolic Rates for Ten Male and Ten Female Subjects at Each of Three Environmental Temperatures

I Hourly Changes in Metabolic Rate (Btu/hr)

	1st-2nd Hour		2nd-3rd Hour		1st-3rd Hour	
Temp.	Males	Females	Males	Females	Males	Females
66	- 8.9	6.9	16.2	- 5.2	7.3	1.7
72	18.4	12.8	0.8	- 3.4	19.2	9.4
78	13.6*	- 4.7	-22.0*	13.1	- 8.4	8.4
Grand Mean#	7.7	5.0	- 1.7	1.2	6.0	6.5

II Hourly Changes in Metabolic Rate (Btu/hr/ft^2)

	1st-2nd Hour		2nd-3rd Hour		1st-3rd Hour	
Temp.	Males	Females	Males	Females	Males	Females
66	-0.52	0.44	0.82	-0.31	0.30	0.14
72	0.86	0.80	0.08	-0.26	0.94	0.54
78	0.67*	-0.26	-1.07*	0.70	-0.39	0.43
Grand Mean#	0.34	0.33	-0.06	0.04	0.28	0.37

* Significant t ratio at the 5% probability level

\# Grand Mean = The combined average of all three temperatures

Table 6

Mean Hourly Changes in Heart Rate and Metabolic Rates for Ten Males and Ten Females at the High, Medium and Low Levels of Activity.

I Hourly Changes in Walking Metabolic Rate (Btu/hr)

Activity Level	1st-2nd Hour		2nd-3rd Hour		1st-3rd Hour	
	Males	Females	Males	Females	Males	Females
High	6.8	31.5*	9.7	-19.5	16.5	12.0
Medium	48.0*	42.8	15.7	12.1	63.7*	54.9
Low	51.5*	-1.3	12.2	8.4	63.7*	7.1
Grand Mean#	35.4	24.3	12.5	0.3	48.0	24.7

II Hourly Changes in Walking Metabolic Rate (Btu/hr/lb)

Activity Level	1st-2nd Hour		2nd-3rd Hour		1st-3rd Hour	
	Males	Females	Males	Females	Males	Females
High	0.05	0.22*	0.05	-0.13	0.10	0.09
Medium	0.28*	0.34	0.11	0.08	0.40*	0.42
Low	0.29*	0.00	0.07	0.04	0.35*	0.04
Grand Mean#	0.21	0.19	0.08	0.00	0.28	0.18

III Hourly Changes in Standing Metabolic Rate (Btu/hr)

Activity Level	1st-2nd Hour		2nd-3rd Hour		1st-3rd Hour	
	Males	Females	Males	Females	Males	Females
High	-22.1*	-5.1	-13.0	-3.3	-35.1*	-8.4
Medium	9.1	0.1	-11.5	-10.9*	-2.4	-10.8
Low	14.5	-10.5	1.1	-9.5	15.6	-20.0*
Grand Mean#	0.5	-5.2	-7.8	-7.9	-7.3	-13.1

Table 6 Continued

IV Hourly Changes in Standing Metabolic Rate (Btu/hr/ft^2)

Activity Level	1st-2nd Hour Males	Females	2nd-3rd Hour Males	Females	1st-3rd Hour Males	Females
High	-0.61	-0.29	-0.61	-0.11	-1.21	-0.21
Medium	0.44	-0.11	-0.53	-0.62*	-0.09	-0.63
Low	0.73	-0.69	0.01	-0.47	0.76	-1.17*
Grand Mean#	0.19	-0.33	-0.37	-0.40	-0.18	-0.67

V Hourly Changes in the Average Metabolic Rate (Btu/hr)

Activity Level	1st-2nd Hour Males	Females	2nd-3rd Hour Males	Females	1st-3rd Hour Males	Females
High	-7.7	13.1	-1.6	-11.4	-9.3	1.7
Medium	22.2*	14.3	-2.5	-3.2	19.7	11.1
Low	20.6*	-9.2	3.3	-6.3	23.9*	-15.5*
Grand Mean#	11.7	6.1	-0.3	-7.0	11.4	-0.9

VI Hourly Changes in Heart Rate Immediately Prior to a Walk (bpm)

Activity Level	1st-2nd Hour Males	Females	2nd-3rd Hour Males	Females	1st-3rd Hour Males	Females
High	4.8	6.0	-0.8	-1.6	4.0	4.4
Medium	1.4	0.8	1.6	-2.0	3.0	-1.2
Low	-3.8	-0.8	3.2	4.8*	-0.6	4.0
Grand Mean#	0.8	2.0	1.3	0.4	2.1	2.4

Table 6 Concluded

VII Hourly Changes in Heart Rate Immediately after a Walk (bpm)

Activity Level	1st-2nd Hour		2nd-3rd Hour		1st-3rd Hour	
	Males	Females	Males	Females	Males	Females
High	1.8	6.8	-2.8	5.6	-1.0	12.4*
Medium	-0.8	-1.4	3.4	5.0	2.6	3.6
Low	0.6	-7.2*	3.8	2.2	4.4	-5.0
Grand Mean#	0.5	-0.6	1.5	4.3	2.0	3.7

* Significant t ratio at the 5% probability level

\# Grand Mean = The combined average of all three activity levels

Table 7

Analysis of Variance for the Sedentary Activity
Using Two Indices of Metabolic Rate

Variable	Source	DF	1st Hour F Ratio	2nd Hour F Ratio	3rd Hour F Ratio
I Metabolic Rate (Btu/hr)	Temperature	2	0.263	0.765	1.509
	Sex	1	56.029***	46.680***	74.125***
	Temp X Sex	2	0.557	1.516	0.107
	Error	54			
	Total	59			

Variable	Source	DF	1st Hour F Ratio	2nd Hour F Ratio	3rd Hour F Ratio
II Metabolic Rate (Btu/hr/ft^2)	Temperature	2	0.382	1.733	1.505
	Sex	1	13.841***	11.964***	19.762***
	Temp X Sex	2	0.137	0.954	0.305
	Error	54			
	Total	59			

Variable	Source	DF	1st Hour F Ratio	2nd Hour F Ratio	3rd Hour F Ratio
III Hourly Changes in Metabolic Rate (Btu/hr)	Temperature	2	1.020	0.555	1.298
	Sex	1	0.078	0.161	0.004
	Temp X Sex	2	1.057	4.498*	1.241
	Error	54			
	Total	59			

Table 7 Concluded

Variable	Source	DF	1st-2nd Hr F Ratio	2nd-3rd Hr F Ratio	1st-3rd Hr F Ratio
IV Hourly Changes in Metabolic Rate ($Btu/hr/ft^2$)	Temperature	2	1.027	0.419	1.204
	Sex	1	0.001	0.059	0.050
	Temp X Sex	2	1.156	4.366*	0.918
	Error	54			
	Total	59			

* = Significant at the 5% probability level
** = Significant at the 1% probability level
*** = Significant at the 0.2% probability level

Table 8

Analysis of Variance for the High, Medium and Low Levels of Activity

Variable	Source	DF	1st Hour F Ratio	2nd Hour F Ratio	3rd Hour F Ratio
I Metabolic Rate While Walking (Btu/hr)	Sex	1	10.173**	10.370**	10.520**
	Individuals: Sex	18			
	Activity Level	2	1.525	1.307	3.260
	Sex X AL	2	0.678	1.617	0.858
	(Inds: Sex) X AL	36			
	Total	59			
II Metabolic Rate While Walking (Btu/hr/lb)	Sex	1	1.815	1.493	1.095
	Individuals: Sex	18			
	Activity Level	2	1.928	1.202	2.767
	Sex X AL	2	1.151	2.056	1.324
	(Inds: Sex) X AL	36			
	Total	59			
III Metabolic Rate While Standing (Btu/hr)	Sex	1	35.810***	42.292***	35.077***
	Individuals: Sex	18			
	Activity Level	2	1.917	12.287***	11.548***
	Sex X AL	2	2.881	0.163	1.472
	(Inds: Sex) X AL	36			
	Total	59			

Table 8 Continued

Variable	Source	DF	1st Hour F Ratio	2nd Hour F Ratio	3rd Hour F Ratio
IV Metabolic Rate While Standing (Btu/hr/ft^2)	Sex	1	22.151***	18.203***	26.933***
	Individuals: Sex	18			
	Activity Level	2	2.037	11.366***	10.557***
	Sex X AL	2	3.116	0.199	1.077
	(Inds: Sex) X AL	36			
	Total	59			
V Average Metabolic Rate (Btu/hr)	Sex	1	17.834***	19.067***	17.234***
	Individuals: Sex	18			
	Activity Level	2	331.891***	406.694***	364.450***
	Sex X AL	2	1.873	8.036**	6.824**
	(Inds: Sex) X AL	36			
	Total	59			
			Btu/hr	Btu/hr/ft^2	% of Heat Prod
VI Evaporative Heat Loss	Sex	1	3.345	1.786	0.333
	Individuals: Sex	18			
	Activity Level	2	56.159***	62.415***	0.245
	Sex X AL	2	0.015	0.290	1.793
	(Inds: Sex) X AL	36			
	Total	59			

Table 8 Continued

Variable	Source	DF	Pre-Test	Post-Test	Post-Test - Pre-Test
VII Heart Rate Pre-Test and Post-Test (bpm)	Sex	1	3.346	4.960*	0.876
	Individuals: Sex	18			
	Activity Level	2	2.027	1.879	0.349
	Sex X AL	2	1.055	0.601	1.541
	(Inds: Sex) X AL	36			
	Total	59			

			1st Hour	2nd Hour	3rd Hour
VIII Heart Rate Immed. Prior to a Walk (bpm)	Sex	1	9.687**	6.161*	9.634**
	Individuals: Sex	18			
	Activity Level	2	2.931	0.213	1.781
	Sex X AL	2	0.482	0.317	1.781
	(Inds: Sex) X AL	36			
	Total	59			

			1st Hour	2nd Hour	3rd Hour
IX Heart Rate Immed. after a Walk (bpm)	Sex	1	9.197**	8.927**	8.847**
	Individuals: Sex	18			
	Activity Level	2	2.034	1.307	0.215
	Sex X AL	2	2.455	0.209	0.131
	(Inds: Sex) X AL	36			
	Total	59			

Table 8 Continued

Variable	Source	DF	1st-2nd Hr	2nd-3rd Hr	1st-3rd Hr
X Hourly Changes in Walking Metabolic Rate (Btu/hr)	Sex	1	0.738	0.762	1.793
	Individuals: Sex	18			
	Activity Level	2	0.991	0.766	2.381
	Sex X AL	2	1.997	0.417	0.980
	(Inds: Sex) X AL	36			
	Total	59			
XI Hourly Changes in Walking Metabolic Rate (Btu/hr/lb)	Sex	1	0.063	0.910	0.906
	Individuals: Sex	18			
	Activity Level	2	0.948	0.809	2.242
	Sex X AL	2	1.346	0.318	0.748
	(Inds: Sex) X AL	36			
	Total	59			
XII Hourly Changes in Standing Metabolic Rate (Btu/hr)	Sex	1	0.535	0.000	1.043
	Individuals: Sex	18			
	Activity Level	2	2.966	0.324	1.705
	Sex X AL	2	3.439*	0.679	3.954*
	(Inds: Sex) X AL	36			
	Total	59			

Table 8 Continued

Variable	Source	DF	1st-2nd Hr	2nd-3rd Hr	1st-3rd Hr
XIII Hourly Changes in Standing Metabolic Rate (Btu/hr/ft^2)	Sex	1	1.533	0.004	3.435
	Individuals: Sex	18			
	Activity Level	2	1.045	0.289	0.412
	Sex X AL	2	1.709	0.572	3.298*
	(Inds: Sex) X AL	36			
	Total	59			
XIV Hourly Changes in Average Metabolic Rate (Btu/hr)	Sex	1	0.066	1.048	3.457
	Individuals: Sex	18			
	Activity Level	2	1.468	0.213	1.528
	Sex X AL	2	3.474*	0.215	2.651
	(Inds: Sex) X AL	36			
	Total	59			
XV Hourly Changes in Heart Rate Immediately Prior to a Walk (bpm)	Sex	1	0.186	0.199	0.011
	Individuals: Sex	18			
	Activity Level	2	3.856*	2.654	1.089
	Sex X AL	2	0.210	0.590	1.779
	(Inds: Sex) X AL	36			
	Total	59			

Table 8 Concluded

Variable	Source	DF	1st-2nd Hr	2nd-3rd Hr	1st-3rd Hr
XVI Hourly Changes in Heart Rate Immediately after a Walk (bpm)	Sex	1	0.217	1.362	0.427
	Individuals: Sex	18			
	Activity Level	2	2.082	0.321	1.982
	Sex X AL	2	1.401	1.061	7.129**
	(Inds: Sex) X AL	36			
	Total	59			

* = Significant at the 5% probability level
** = Significant at the 1% probability level
*** = Significant at the 0.2% probability level

TABLE 9

Regression Equation Values Used in Predicting Metabolic Rate (MR) for Two Hypothetical Models and Supportive Statistics

Activity and Variable (Btu/hr)	Sex	Model I: MR = $a_1(Wt)^{b_1}$					Model III: MR = $a_3(Wt)^{b_3}(Ht)^{b_4}$							
		a_1	b_1	S_{b_1}	t_{b_1}	r	a_3	b_3	b_4	S_{b_3}	S_{b_4}	t_{b_3}	t_{b_4}	R
Sedentary Metabolic Rate	M	97.00	0.274	0.112	2.45*	0.42	86.28	0.248	0.171	0.146	0.603	1.69	0.28	0.42
	F	33.75	0.449	0.145	3.10**	0.51	0.00605	0.082	2.494	0.175	0.814	0.47	3.06**	0.67
	M+F	12.30	0.670	0.092	7.28***	0.69	0.01135	0.207	2.207	0.131	0.494	1.58	4.46***	0.78
High: Standing Metabolic Rate	M	26.19	0.573	0.137	4.18**	0.85	0.102	0.602	1.276	0.894	0.416	6.74***	3.07*	0.94
	F	28.98	0.517	0.137	3.78**	0.80	10.719	0.473	0.290	0.200	0.881	2.37*	0.33	0.80
	M+F	8.96	0.772	0.122	6.32***	0.83	0.0498	0.572	1.473	0.116	0.452	4.94**	3.26*	0.90
Medium: Standing Metabolic Rate	M	17.73	0.637	0.177	3.60**	0.78	1486.5	0.619	-1.026	0.172	0.808	3.61**	-1.27	0.83
	F	51.81	0.385	0.100	3.86**	0.81	12.43	0.322	0.417	0.143	0.650	2.25	0.64	0.82
	M+F	10.25	0.732	0.125	5.86***	0.81	1.614	0.660	0.525	0.150	0.605	4.39**	0.87	0.82
Low: Standing Metabolic Rate	M	56.64	0.401	0.132	3.03*	0.73	648.6	0.388	-0.561	0.135	0.632	2.87*	-0.89	0.76
	F	87.98	0.371	0.121	3.07*	0.74	253.7	0.441	-0.446	0.170	0.733	2.60*	-0.61	0.75
	M+F	19.03	0.604	0.113	5.34***	0.78	2.374	0.524	0.590	0.133	0.518	3.95**	1.14	0.80

TABLE 9 Concluded

Activity and Variable (Btu/hr)	Sex	Model I: $MR = a_1(Wt)^{b_1}$					Model III: $MR = a_3(Wt)^{b_3}(Ht)^{b_4}$							
		a_1	b_1	S_{b_1}	t_{b_1}	r	a_3	b_3	b_4	S_{b_3}	S_{b_4}	t_{b_3}	t_{b_4}	R
High; Walking Metabolic Rate	M	47.25	0.697	0.140	4.98**	0.87	0.436	0.722	1.077	0.122	0.559	5.94***	1.93	0.92
	F	21.93	0.831	0.087	9.61***	0.96	21.78	0.937	-0.675	0.112	0.487	8.37***	-1.39	0.97
	M+F	16.81	0.893	0.086	10.36***	0.92	0.789	0.774	0.870	0.089	0.343	8.69***	2.54*	0.95
Medium; Walking Metabolic Rate	M	27.51	0.796	0.150	5.31***	0.88	6.113	0.802	0.348	0.158	0.735	5.09**	0.47	0.89
	F	23.31	0.819	0.150	5.46***	0.89	7.548	0.768	0.330	0.220	0.986	3.48*	0.34	0.89
	M+F	18.09	0.875	0.090	9.68***	0.92	3.063	0.805	0.506	0.107	0.423	7.54***	1.20	0.92
Low; Walking Metabolic Rate	M	27.26	0.796	0.130	6.12***	0.91	81.17	0.790	-0.251	0.139	0.642	5.69***	-0.39	0.91
	F	23.92	0.809	0.149	5.43***	0.89	451.9	0.947	-0.867	0.202	0.857	4.69**	-1.01	0.90
	M+F	16.49	0.891	0.088	10.14***	0.92	12.30	0.879	0.083	0.106	0.410	8.27***	0.20	0.92

r = Product Moment Correlation Coefficient
R = Multiple Correlation Coefficient
S_{bi} = Standard Error of b_i

t_{bi} = t Ratio = $\frac{bi}{S_{bi}}$

* = Significant at the 5% Probability Level
** = Significant at the 1% Probability Level
*** = Significant at the 0.1% Probability Level

Wt = Body Weight (lb)
Ht = Body Height (in)

TABLE 10

Regression Equation Values Used in Predicting Evaporative Heat Loss (E) for Two Hypothetical Models and Supportive Statistics

Activity and Variable (Btu/hr)	Sex	Model I: $E = a_1(Wt)^{b_1}$					Model III: $E = a_3(Wt)^{b_3}(Ht)^{b_4}$							
		a_1	b_1	S_{b_1}	t_{b_1}	r	a_3	b_3	b_4	S_{b_3}	S_{b_4}	t_{b_3}	t_{b_4}	R
High: Evap. Heat Loss	M	0.260	1.467	0.405	3.61**	0.77	16.24	1.445	-0.951	0.460	2.140	3.14*	-0.44	0.77
	F	0.0299	1.882	0.338	5.57***	0.89	1.140	2.038	-1.012	0.487	2.150	4.19**	-0.47	0.90
	M+F	0.1615	1.567	0.233	6.73***	0.85	2.440	1.672	-0.770	0.279	1.109	5.99***	-0.71	0.85
Medium: Evap. Heat Loss	M	0.2964	1.396	0.550	2.54*	0.67	3.657×10^6	1.332	-3.781	0.505	2.381	2.63*	-1.59	0.77
	F	0.0042	2.261	0.269	8.41***	0.95	0.410	2.464	-1.337	0.381	1.733	6.46***	-0.77	0.95
	M+F	0.0399	1.795	0.261	6.88***	0.85	3.882	1.973	-1.300	0.312	1.253	6.33***	-1.04	0.86
Low: Evap. Heat Loss	M	0.1097	1.548	0.400	3.87**	0.81	47.67	1.516	-1.397	0.415	1.941	3.66**	-0.72	0.82
	F	0.0590	1.653	0.574	2.88*	0.71	6.892×10^8	2.720	-6.810	0.581	2.504	4.69**	-2.72*	0.87
	M+F	0.0422	1.730	0.289	5.99***	0.82	7.062	1.927	-1.453	0.339	1.324	5.69***	-1.10	0.83

r = Product Moment Correlation Coefficient
R = Multiple Correlation Coefficient
S_{bi} = Standard Error of b_i

t_{bi} = t Ratio = $\frac{bi}{S_{bi}}$

* = Significant at the 5% Probability Level
** = Significant at the 1% Probability Level
*** = Significant at the 0.1% Probability Level

Wt = Body Weight (lb)
Ht = Height (in)

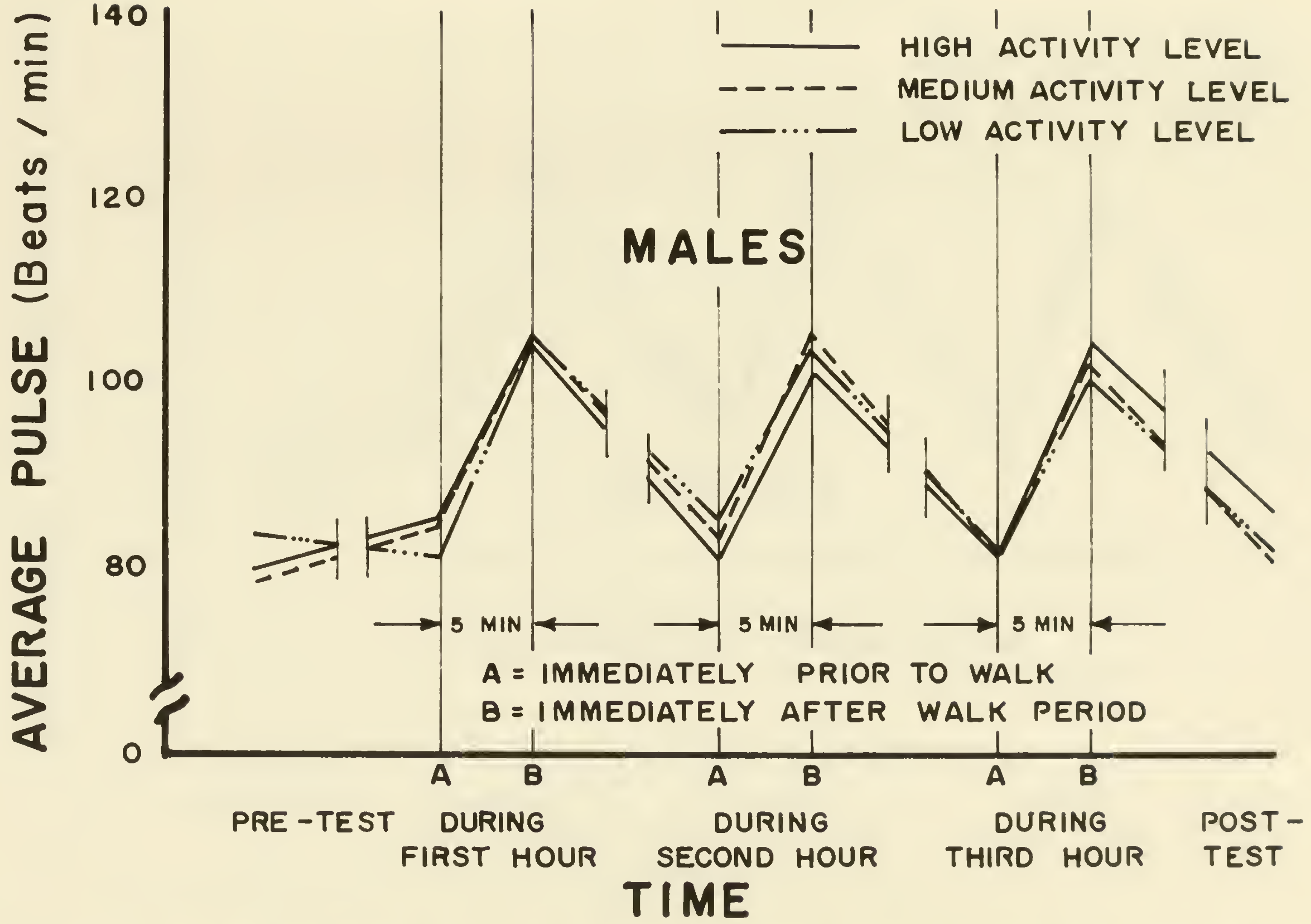

Figure 6. Heart rate variations for the males at the low, medium and high levels of activity as a function of the time in the test environment.

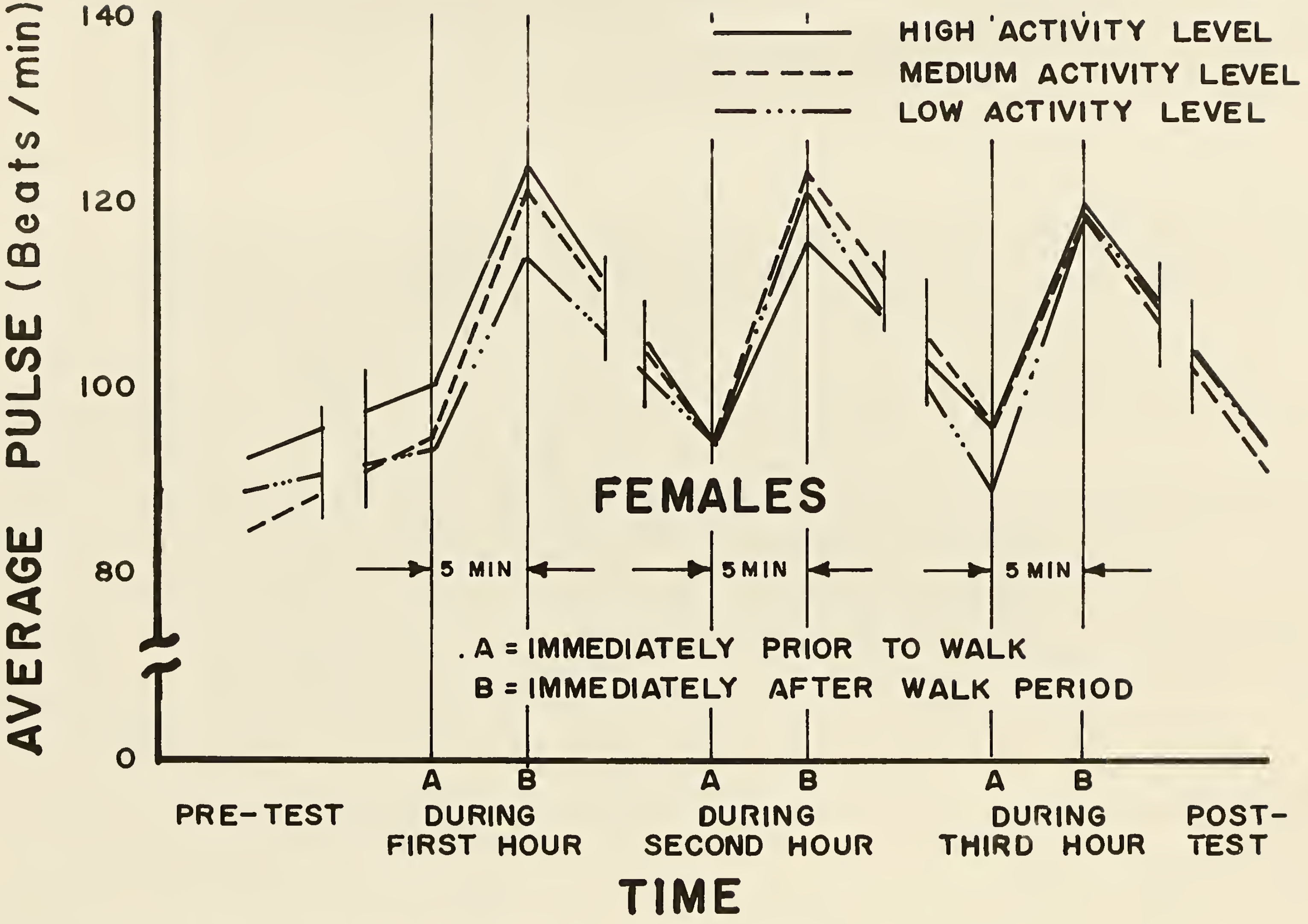

Figure 7. Heart rate variations for the female at the low, medium and high levels of activity as a function of the time in the test environment.

reported.

The sedentary results indicated that:

1. Environmental temperature over the range examined (66 to 78F) had no significant effect on sedentary metabolic rate or the hourly changes in metabolic rate (Btu/hr and Btu/hr/ft^2) of either men or women at any of the three hours.
2. The males indicated a statistical difference at the 5% probability level in their metabolic rates between the first and second hours and between the second and third hours at the environmental temperature of 78F on both a Btu/hr and a Btu/hr/ft^2 basis.
3. The three hour average metabolic rates were quite consistent for the three environmental temperatures.
4. There were no temperature by sex interactions on metabolic rate at any of the three hours, however, there were temperature by sex interactions in the change in metabolic rate between the second and third hours on both a Btu/hr and a Btu/hr/ft^2 basis.
5. The differences in metabolic rate between males and females on both a Btu/hr and a Btu/hr/ft^2 basis were highly significant at the 0.2% probability level, however, the F-ratio is much lower on a Btu/hr/ft^2 basis.
6. The differences in the hourly changes in metabolic rate on either basis between males and females were not significant.
7. The third hour average metabolic rates for all three temperatures were 389 and 301 Btu/hr for the males and females respectively.
8. The regression equations (Model I and Model III) for predicting sedentary metabolic rate showed a larger correlation coefficient for the females than for the males; however, the standard error

of the exponents was greater for the females than for the males.

9. The regression equations (Model I and Model III) had the highest correlation coefficients and the smallest standard error of the exponents for the males and females combined.
10. Model III provided a better prediction of metabolic rates for the females and for the combined males and females, than Model I, because the t-ratio of the exponent applied to height was significant.
11. The results of the regression equation for Model II, $MR = a_2 (Ht)^{b2}$ were not reported, as they were not as consistent as were those obtained for Model I or Model III.

The results of the activity phase indicated that:

1. None of the variables examined showed significant change from the second hour of testing to the third hour of testing with the exception of the females' metabolic rate during the stand period at the medium activity level and their heart rate immediately prior to a walk at the low activity level. However, the first hour was found to be significantly different from the second or third hours in nearly a fourth of the variables examined at the 5% probability level.
2. There was an effect of the level of activity on metabolic rate during the stand periods for the second and third hours only and on evaporative heat loss (on both a Btu/hr and a Btu/hr/ft^2 basis) on the average metabolic rate and on the change in heart rate immediately prior to a walk between the first and second hours.

3. Activity level did not have any significant effect on the metabolic rate of the walking period on either a Btu/hr or a Btu/hr/lb basis, on the evaporative heat loss as a percent of the total heat production, on heart rate, or on the hourly changes in metabolic rate or heart rate with the exception of the change in heart rate immediately prior to a walk between the first and second hours as noted above.
4. At all hours tested and at all activity levels there was a significant effect of sex on the walking period metabolic rate on a Btu/hr basis, on the standing period metabolic rate on both a Btu/hr and Btu/hr/ft^2 basis, on the average metabolic rates, on the heart rate immediately prior to a walk and after a walk, and on post-test heart rate.
5. There was no significant difference between males and females at any hour or at any activity level for the walk cycle on a Btu/hr/lb basis and the standard deviations from the means were relatively small.
6. There was no significant effect of sex on evaporative heat loss on either a Btu/hr or a Btu/hr/ft^2 basis, on the evaporative heat loss as a percent of the total heat production, on the pre-test heart rate, or on any of the hourly changes in metabolic rate or heart rate.
7. There were no interaction effects between sex and the level of activity on evaporative heat loss or any of the metabolic rates except for the average metabolic rate during the second and third hours, however, there were some sporadic interaction

effects on the hourly changes in metabolic rate and heart rate;

8. The third hour average metabolic rates for the low, medium, and high levels of activity were 622, 829, and 1061 Btu/hr respectively for the males and 492, 653, and 826 respectively for the females.
9. In general the results of the regression analysis for predicting the standing and walking metabolic rates and the evaporative heat losses were consistent and accurate for Models I and III; however, the results of Model II showed excessive scatter and inconsistencies and, therefore, were not reported.
10. The correlation coefficients in Models I and III for the metabolic rates while standing and walking and for the evaporative heat losses were relatively large ranging from 0.67 to 0.97.
11. The accuracy of the equations obtained from Model I was comparable to that from Model III except for the males' and the combined males' and females' standing metabolic rates at the high activity level, the males' and females' combined walking metabolic rate at the high activity level, and the females' evaporative heat loss at the low activity level.
12. None of the regression models for the combined convective and radiative heat loss gave consistent or accurate equations; therefore, these results were not reported.

DISCUSSION

The criteria defined by Rohles (91) regarding the factors which influence environmental research involving human subjects were considered in this study. One of the reciprocative factors is activity; as it increases, heat production also increases. This study investigated this factor and its relationship to thermal comfort. Other reciprocative factors such as clothing, exposure time, and the number of subjects by sex were identical for each thermal condition in the sedentary tests and for each level of activity in the activity studies. The organismic factors of biological rhythmicity and age were accounted for by randomly conducting the tests in the afternoons and evenings and by choosing subjects from the normal age range of college students. However, it is interesting to note that Seltzer (92) reported that age showed no association with the amount of oxygen consumed during moderate exercise. Morning tests were avoided, since previous work indicated the thermal comfort results of morning tests were significantly different from afternoon and evening tests (87). The physical factors, [temperature, humidity, air movement, radiation, Area-Volume (room size), light, color and sound] were all controlled and uniform for these studies. The metabolic rates or energy expenditure rate of the subjects was obtained by measuring the oxygen consumption rate.

In measuring metabolic rates during exercise, the method is critical. The use of steady-state slopes during the walk and standing periods was judged to be the most accurate. With this method, the attainment of a steady state rate of oxygen consumption is mandatory. Karpovich (64) reported that as long as an exercise is not strenuous and a steady state is attained, the energy costs of an exercise may be found without measuring the recovery oxygen. Webb (101) stated that when a man begins to work, metabolism and heart rate reach new plateaus within one to three minutes. Astrand and Salfin (3) reported that the time necessary for oxygen consumption to reach steady state during exercise depended upon the severity of the exercise. The times ranged from one minute for extremely heavy exercise to five minutes for light exercise. Preliminary testing at this laboratory indicated that steady-state oxygen consumption was reached in one and a half to two minutes after the subject began walking and two to three minutes after beginning to stand following a walk. Therefore, steady state slopes were used to determine the metabolism while walking and while standing and the results are in agreement with predictions made from the work of Ford and Hellerstein (34).

The respiratory quotient was not measured. Previous work by Campbell et al. (21), Best and Taylor (10), Asmussen (2), Issekutz and Rodahl (61), Fahnestock et al. (31), and Benedict and Cathcart (8) have shown that, for sedentary subjects, the RQ value of 0.82 to 0.85 is within very reasonable tolerance. Because most investigators reported 0.82, this value was chosen for the sedentary tests. For reasonable levels of activity (600 to 1200 Btu/hr), some of the above researchers reported RQ's from 0.70 to nearly 1.00 with the majority of them between 0.80 and 0.90. Therefore an RQ of 0.85 was chosen for the activity studies, as there is a tendency for the RQ to increase during exercise. In a range of RQ's from 0.70 (complete combustion of fats only) to 1.00 (complete combustion of carbohydrates only), the maximum error induced in the metabolic rate by assuming an RQ of 0.85 is 3.74%. In the normal range of 0.80 to 0.90, the error would be less than 1.5%. The author believed this to be negligible as did Fahnestock et al. (31). This assumption was further supported by the large number of metabolic rates measured in these experiments which would tend to average the RQ between the two extremes.

In the experimental design, the activity tests were to be conducted in a thermally neutral environment. Therefore, it was essential to establish the effect environmental conditions have on metabolic rate; thus, the sedentary tests were designed to investigate this effect, as the literature showed inconclusive results. Iampietro et al. (57) reported relative humidity and temperature had significant effects on heat production when healthy young men were exposed nude to the cold (50 and 60 F and 30 and 95% RH). The conditions, however, would have caused shivering, but the relative humidity influence was not fully understood. However, in another report, Iampietro et al. (58) found that lightly clothed men exposed to temperatures of 40 and 50 F and relative humidities of 30 and 100% showed that relative humidity had no effect on oxygen consumption but that temperature had a significant effect. Again, shivering would be the cause of this effect.

Suggs and Splinter (94) reported an interaction effect of temperature and humidity on metabolism, the degree of the effect seems too large. Brouha et al. (13) reported that five men and one woman working in various environments showed a significantly lower metabolism (13% less) in a warm dry climate (99 F -25% RH). This condition would cause a radiative and convective heat gain on the body, and this might possibly be the cause of this finding. Yet another report by Brouha et al. (14) on five men and one woman working at intermittent periods of thirty minutes, including one test at 99 F dry bulb temperature and

25% RH, stated that "in both cool and warm environments, the level of metabolism during work was maintained at approximately the same magnitude throughout the experiment." Williams et al. (106) reported that acclimatized men working on a bicycle ergometer showed significantly lower metabolism in hot climates (97 F dry bulb and 93 F wet bulb temperature) than in comfortable (70 F) conditions. Consolazio et al. (23) reported a completely opposite finding to the first reported findings of Brouha et al. (13) and those of Williams et al. (106). They found that men working in a warm environment (100 F - 30% RH) showed a significantly higher metabolic rate than at 70 F.

Fahnestock et al. (30) reported that there were no significant differences in the energy expenditures in two environments (75 F - 45% RH and 95 F - 50% RH) employed in sedentary activity tests or any of four work rates (approximately 600, 800, 1000, and 1200 Btu/hr). DuBois (27) reported that metabolic rate is not a function of temperature over a rather broad comfort range. Fahnestock and Werden (32) reported that sedentary metabolism is practically constant over the range of 65-95 F dry bulb temperature. Passmore and Durnin (89) reported that Consolazio and Kark found that, for men working at a fixed rate on a bicycle ergometer, the metabolism varied by less than 4% over the temperature range -15 to +32 C.

Malhorta et al. (75) found there were no significant differences in the change in basal metabolic rate of seven young adult males between winter and summer, nor were there any differences between the rates of energy expenditure required to accomplish different exercises when these rates were normalized for body weight between winter and summer.

Edholm et al. (28) reported that, with sixteen men working in hot and cold environments there did not appear to be any significant change in metabolic rate throughout the experiment as a function of the environmental conditions. Houghten et al. (55) indicated that, for men seated at rest and working at 850 Btu/hr, their metabolism was constant over a broad Effective Temperature range but there was a negligible effect of relative humidity on metabolism. Winslow et al. (110) reported that, for unclothed subjects in a semi-reclining position subjected to turbulent air movement of fifteen to twenty feet per minute, two males showed approximately 20% day to day variations in their metabolic rate but that, over a wide range of environmental conditions, the metabolism remained approximately constant. For persons at complete rest, nude, and in minimal air movement, Hardy and DuBois (41) reported that women showed some variation of metabolism with respect to the environment while men showed a constant metabolism over a range from 72 F to 95 F. The metabolism of women was similar to that of the men in the zone from 72 to 81 F but demonstrated a drop at temperatures above 81 F. Hardy and Milhorat (40) reported similar findings on two different women and also stated that the women did not begin to sweat until the calorimeter was about 4 F above the threshold for sweating in the men. In addition, the amount of sweating was less for the women. In general, it appeared that metabolic rate is only affected by extreme temperatures, where thermal comfort would not exist, and the results of the sedentary studies indicated that the environmental temperature range of 66 - 78 F at relative humidities of 50% had no significant effect on sedentary metabolic rate. Therefore, the low, medium and high activities were performed in a thermally neutral environment in order that a more meaningful heat loss analysis might be performed.

In general, the standard deviation as a percent of the mean value was higher for women than for men in the sedentary tests. The rather high deviations of the women are not fully understood. The third hour indicated the smallest percent deviation on both a Btu/hr and a Btu/hr/ft^2 basis for both the males and females. Based on these findings and the results of other work at the Institute (which indicated that body heat storage during sedentary activity will become negligible after two hours or more), the third hour results should be the most accurate even though they differ very slightly from the total test period average. The results of the sedentary study were in excellent agreement with the value of 400 Btu/hr for the average man sitting quietly given in the ASHRAE Handbook of Fundamentals (1), and the Bioastronautics Data Book (102). However, the results were somewhat higher than the average sedentary metabolic rate of 334 Btu/hr for six college-age males reported by Fahnestock et al. (30). The third hour grand mean value of 301 Btu/hr for the females is 77.4% of the male value and this was in good agreement with the figure of 80% of the male value which is sometimes cited.

The males' hourly difference which occurred in the sedentary metabolic rate at 78 F was a result of the second hour rate being about 3 and 5 percent less than the first and third hour rates respectively. While this is a rather small percent in engineering terms, it nevertheless shows the power of the statistical analysis performed and further supports the non-significant effect of environmental temperature on metabolic rate. F. L. Harmon (30) also reported statistically significant hourly variations in metabolic rates but not statistically significant daily variation. However, Edholm et al. (28) reported considerable day to day variations during work in both cool and hot environments but no significant changes over a two week period.

The results of the analysis of variance for the sedentary activity given in Table 7 were uniform and consistent with the anticipated findings with the exception of the temperature by sex interaction of the second to third hourly change. This finding was due to the males' higher metabolic rate during the second hour at 66 F and lower metabolic rate during the second hour at 78 F. The results of the females at this hour were completely opposite to the male results and, hence, the temperature by sex interaction. The practical significance of this finding is probably negligible.

In the low, medium and high activities, the standing and walking metabolic rates were reported separately and later combined to give the average metabolic rate for the given activity. The metabolic rate while walking was normalized for a unit of clothed body weight. Swift and Fisher (95) reported that body size was an important consideration in the determination of the energy costs of physical activity and Seltzer (92) reported that the weight had the highest coefficient of correlation between anthropometric measurements and oxygen intake during severe exercise. Robinson (90) reported that, for men walking on a grade, the metabolic rate was closely related to body weight. Wyndham et al. (113) reported that "the rate of oxygen consumption in physical tasks where the gross body weight is lifted against gravity has been shown to be closely related with gross body weight."

Some authors determine a net cost of performing an exercise. For a walking exercise, this would be accomplished by subtracting the metabolic rate while standing from the metabolic rate while walking. This analysis was omitted, because the emphasis was directed towards measuring the gross heat production, and the corresponding heat loss and their relationship to thermal comfort. The third hour average metabolic rates while walking were 1599 Btu/hr and 9.89 Btu/hr/lb for the males and 1277 Btu/hr and 9.57 Btu/hr/lb for the females.

The results of the individual metabolic rates while walking and while standing were proportioned to the amount of time per hour each of these activities was performed for each of the three levels of activity. This resulted in an average metabolic rate for each of the three levels of activity. For example in the high activity level the subjects spent one half of the hour walking and one half of the hour standing, therefore, the third hour males' average metabolic rate (Btu/hr) would be $\frac{1}{2}$ x 1641 + $\frac{1}{2}$ x 480 = 1061 Btu/hr. The results of the first, second, and third hour average metabolic rates were combined to give an average for the second and third hours and for the first, second and third hours. However, the values never differed from the third hour average more than 2%.

The third hour average metabolic rates were plotted versus the thermally neutral zones established by Nevins et al. (87) and McNall et al. (81) for the four levels of activity. The thermally neutral zone includes those temperatures within one-half vote of the thermally neutral temperature {based on the seven point thermal sensation ballot reported by McNall et al. (81)}. The result is shown in Figure 5, which indicates the recommended thermal comfort conditions as a function of the metabolic rate for college-age males and females. The 45% relative humidity line in the zone was established for the thermally neutral vote only.

The heart rate data were examined to help determine the physiological stress imposed on the subject. Taylor (98) reported that the level of heart rate during exercise was proportional to the work-load. Brouha *et al*. (14) reported that, in a comfortable environment with alternating work-rest cycles, the heart rate remained relatively stable during the work periods.

The average heart rate results were quite uniform; however, the males were more nearly uniform than the females as can be seen from Figures 6 and 7. Table 11 shows the mean increment in heart rate just prior to a walk and immediately following a five minute walk period for three levels of activity. In general, the results of the heart rate data were similar to those found by McNall *et al*. (81) for the thermal conditions; however, the physiological stress of the women at the high activity level suggested by McNall *et al*. (81) is not as evident in these results. In addition, the results were more uniform and consistent than those of McNall *et al*. (81). All of these tests were conducted in a thermally comfortable environment which would tend to reduce physiological stress. In addition, the heart rate of each subject was measured at the midpoint of each hour. This was possible because of the staggered entering intervals. McNall *et al*. (81) were unable to do this because of the larger number of subjects tested at one time. This would account for the majority of differences in the degree of uniformity and consistency between the present tests and those of McNall *et al*. (81).

Table 11

Mean Increment in Heart Rate During the Five Minute Walk Period for the High, Medium and Low Levels of Activity

Activity	Males 1st Hr	 2nd Hr (Beats Per Minute)	 3rd Hr	Females 1st Hr	 2nd Hr (Beats Per Minute)	 3rd Hr
High	17.8	20.8	22.8	23.6	21.2	24.0
Medium	20.6	22.8	21.0	27.2	29.0	22.0
Low	23.4	19.0	18.4	21.0	27.4	30.0
Grand Mean	20.6	20.9	20.7	23.9	25.9	28.0

With reference to the activity tests, studies performed at this laboratory indicated that body heat storage is negligible after the first hour for any of the three activity levels performed in a comfortable environment. Therefore, it is believed that a change in the amount of heat stored in the body is the major influencing factor of the reported first hour irregularities in metabolic rates. As a result of these findings, the second and third hours were used for discussion and results unless otherwise noted. Even then, it was found that the largest variation between the first and second or third hour is less than 7% for any of the numerous measurements taken, again illustrating the power of the statistical analysis performed.

The effect of the high activity level on the "standing" metabolic rate during the second and third hours can possibly be explained by the fact that a single standing period during the low activity level had a duration of twenty five minutes and for the medium activity level it was ten minutes, While for the high activity level it was only five minutes. A steady-state slope during the standing period was attained in two to three minutes after the completion of a walk period. With the settings on the X-Y recorder adjusted to measure the oxygen consumption of the five minute walking period and up to ten minutes of the standing period an easily defined steady state condition was attainable in the low and medium activities. However, the standing period oxygen consumption rate at the high activity level could be based only on a steady state slope of the last two or three minutes of the five minute period. The trend of this steady-state slope was somewhat higher than those of the low and medium activities, and this difference resulted in the higher metabolic rate during the high activity level standing period. The reason that the first hour did not show this irregularity was that the males' average standing metabolic rate only varied from 445 to 449 Btu/hr over the three levels of activity. After the first hour, it increased for the high activity level and decreased for the medium and low activity levels.

The metabolic rate while walking, when normalized for a unit clothed body weight, was the only metabolic rate which was independent of the subjects' sex. This would indicate that the previously discussed reasoning for such a normalization has ample merit. The effect of the subjects' sex on the heart rate levels immediately prior to a walk and following a walk was expected because McNall _et al._ (81) reported similar findings. However, it is interesting to note that, although there were sex differences in the level of the heart rate, the hourly changes in heart rate were independent of sex. In addition, the hourly changes in metabolic rate were independent of sex.

Sex by activity level interactions were seldom evident. The standing metabolic rate interactions between hours were due to increases in the males' standing metabolic rate after the first hour for the high activity level and decreases for the medium and low activity levels while the females' standing metabolic rate increased with each succeeding hour for all three levels of activity. These same results were the cause of the interaction in the first and second hour change of the average metabolic rate. The interaction effect on the second and third hour average metabolic rates was probably the result of the highly significant effects of both sex and activity level. Practically speaking, this effect does not have any real significance. The interaction of the first and third hour change in heart rate immediately following a walk was the result of the females' change at the low and high activity levels. At the high activity level, the females' heart rate level immediately following a walk continually declined with each hour of exposure. The results of McNall et al. (81) indicated similar findings. The cause of this is not fully understood.

A water balance on each subject was kept for the activity studies only, therefore, a heat loss analysis could be computed for the low, medium and high levels of activity only. Data on evaporative heat loss for sedentary subjects can be found in the ASHRAE Handbook of Fundamentals (1). The analysis of variance on the rate of heat loss by evaporation indicated there was no significant difference between men and women even though the males were 21 to 33% higher on a Btu/hr basis and 10 to 23% higher on a Btu/hr/ft^2 for the high and low activity levels respectively. These figures were in excellent agreement with those reported by McNall et al. (87). The reason for the absence of statistical significance was the high variance from the mean among individuals, even when normalized for unit body area. The evaporative heat loss of Fahnestock et al. (31) was analyzed, and a similar high individual variation, even when normalized for unit body area, was found. The cause of this high subject-to-subject variation is not fully understood. Even though the statistical analysis indicated there was no difference in evaporative heat loss between males and females undergoing these three levels of activity, the large differences in the means suggest that there actually were differences in evaporative heat loss between males and females for a given activity performed in a thermally comfortable environment and that this difference might have been significant if the evaporative heat loss data had been normalized for unit body weight to the 1.70 power as suggested by the results of the Model I regression equations for evaporative heat loss. The evaporative heat loss divided by the average heat production multiplied by 100 yields the percent of the total heat loss due to evaporative heat loss, provided heat production is equal to heat loss. The analysis of variance indicated that this variable was independent of both sex and the level of activity (when performed in thermally comfortable conditions). This suggests that this variable may be an index of thermal comfort when the activity level is above sedentary. Figure 8 illustrates the relationship between the means of the percent of evaporative heat loss and the level of activity.

For heat transfer calculations, the third hour metabolic rates were used, because, as previously stated, the body storage rate was negligible after the first hour at any one of the three levels of activity. In addition, Webb (101) reported that heat production changes rapidly with changes in activity; however, the corresponding changes in heat loss follow more slowly, resulting in a temporal dissociation. Conduction losses were assumed negligible, and the net external mechanical work while standing and while walking was zero. Convection, radiation and evaporation losses are all positive. Therefore, equation (1) reduces to

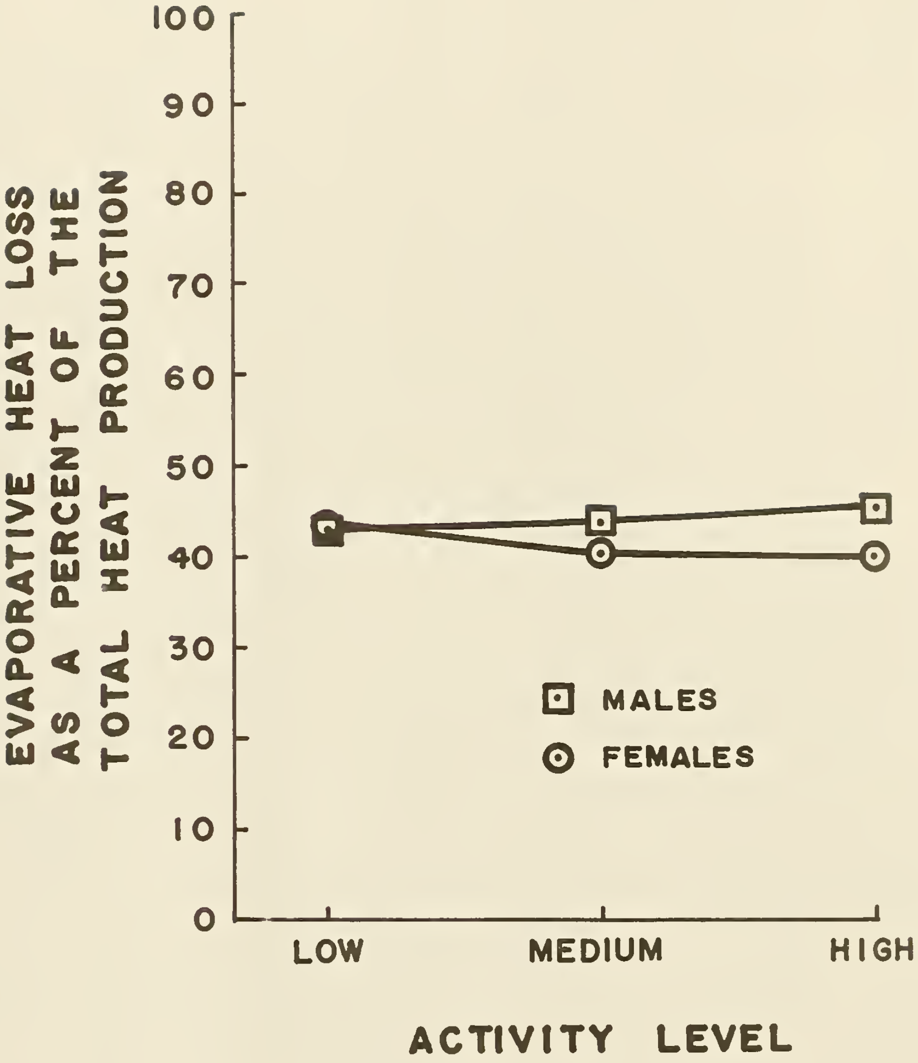

Figure 8. Evaporative heat loss as a percent of the total heat production (metabolic rate) as a function of the activity level for males and females.

$$M = E_v + R + C_v \,. \tag{9}$$

The R + C_v losses were calculated from Humphreys et al. (56) who stated that A. C. Burton reported that

$$R + C_v = 22.8 \cdot \frac{t_s - t_a}{I_c + I_a} \,, \tag{10}$$

where: t_s = Skin temperature, F

t_a = Air temperature, F

I_c = Insulation of clothing, Clo

I_a = Insulation of air, Clo.

The values of t_s were taken from the data compiled by Fanger (33) at this laboratory. A linear regression of his data gave a separate equation for males and females for the mean skin temperature as a function of the metabolic rate per unit body surface area for persons in thermal comfort. Fanger (33) found that there were no statistically significant differences between the linear regression equations for males and females; however, the heat loss analysis of this study was more uniform when the two separate equations were used. The results of this regression analysis were

$$\text{Males: } t_s = 35.56 - 0.0286 \frac{M}{A_{Du}} \tag{11}$$

$$\text{Females: } t_s = 36.14 - 0.0392 \frac{M}{A_{Du}} \,, \tag{12}$$

where: t_s = Mean skin temperature, (°C)

$\frac{M}{A_{Du}}$ = Metabolic rate per unit body surface area (Kcal/hr/m^2).

The results of a comparison between heat production and the heat loss analysis for the average male and female subject participating in the tests are given in Table 12.

Table 12

Metabolic Heat Production Compared to Heat Loss for the Average Male and Female Subject at the Thermal Neutrality Condition for the Low, Medium and High Levels of Activity

Level of Activity	Evaporation (measured) (Btu/hr)		Convection and Radiation (Calculated) (Btu/hr)		Total Heat Loss (Btu/hr)		3rd Hr Heat Production (Measured) (Btu/hr)		Difference (Heat Loss-Heat Produc) (Btu/hr)		Difference (%)	
	Male	Female	Male	Female	Male	Female	Male	Female	Male	Female	Male	Female
Low	294	197	343	306	637	503	622	492	15	11	2.4	2.2
Medium	373	262	443	382	816	654	829	653	-13	1	-1.5	0.2
High	462	368	535	468	997	836	1061	826	-64	10	-6.0	1.2

Total heat loss was computed by adding the measured evaporative loss and the calculated radiation and convection losses. The third hour average heat production was subtracted from this value to indicate the difference between heat loss and heat production. The percent difference determined by dividing the difference by the total heat production and multiplying by 100 were all less than 3% except for the males at the high activity level. This suggests that the assumptions and measurements were reasonably accurate.

The results of the regression analysis were enlightening. In most cases the variable is best described by Model I as evidenced by the small increment of the Model III correlation coefficient over that of Model I. However, Model III should be used instead of Model I whenever the correlation coefficient is appreciably higher than that of Model I. When t_{b_4} is significant it indicates that height contributes something significant to the prediction. The equation whose corresponding coefficient is highest among the male, female or combined should be employed to insure the highest level of predictive accuracy.

The equations for predicting sedentary metabolic rate were acceptable but the correlation coefficients are not so large as those for the standing and walking metabolic rates. The equations for predicting the standing and walking metabolic rates and evaporative heat loss were efficient because of the high correlation coefficients. The exponents for Model I for predicting metabolic rate while standing for the combined males and females ranged from 0.604 to 0.772 for the three levels of activity. The exponents for Model I for predicting the metabolic rate while walking for the combined males and females ranged from 0.875 to 0.893 for the three levels of activity, indicating that the normalization of the walking metabolic rate for unit clothed body weight was quite reasonable and that body weight is the principal factor governing this variable. The exponents for Model I for predicting evaporative heat loss for the combined males and females ranged from 1.567 to 1.795 for the three levels of activity. This suggests that body weight is a principal factor governing the amount of evaporation.

SUMMARY AND CONCLUSIONS

The research reported in this thesis measured the oxygen consumption rates and, hence, the metabolic rates of college-age males and females performing four levels of activity and then correlated these rates with thermal comfort. In addition, heart rate and evaporative heat loss were analyzed. The activity levels studied were as follows: sedentary, in which the subjects sat quietly and studied at tables; low activity, which consisted of performing a modified step test for 5-minutes and standing for 25-minutes; medium activity in which the step test was performed for 5-minutes and standing 10-minutes; high activity in which the step test was performed for 5-minutes and standing 5-minutes.

The sedentary study was performed at three temperatures; 66, 72, and 78 F and the low, medium, and high activities were performed in an environment found to be thermally neutral for these activities by McNall et al. (81). The test period duration was always three hours.

The results showed that:

1. Sedentary metabolic rate is independent of the environmental temperature over the range 66 to 78 F.

2. The third-hour sedentary metabolic rates are the most accurate. The grand means of sedentary metabolic rates for males and females for all three temperatures were 389 and 301 Btu/hr, respectively.

3. The metabolic rate, normalized for clothed body weight while walking in the low, medium and high activity levels, was the only metabolic rate not related to the sex of the subject.

4. The third-hour metabolic rates for the low, medium, and high levels of activity are 622, 829, and 1061 Btu/hr, respectively, for the males and 492, 653, and 826 Btu/hr, respectively, for the females.

5. The metabolic rates were correlated with thermal comfort conditions reported by previous investigators for the same activities, and a proposed thermal comfort zone as a function of metabolic rate was presented.

6. The percent of the total heat production lost by evaporation for the low, medium and high activity levels was independent of sex and the activity level, and, hence, this variable might be an index of thermal comfort.

7. A comparison between measured heat production and calculated heat loss was presented.

8. Equations for predicting metabolic rates for sedentary, standing and walking subjects, based on their height and weight were determined from a regression analysis and presented. These results indicate that the subjects' weight is the principal variable governing walking and standing metabolic rates and evaporative heat losses.

SELECTED BIBLIOGRAPHY

1. ASHRAE Handbook of Fundamentals. 1967, Chapter 7.

2. Asmussen, E. "Muscular Exercise." Handbook of Physiology Sect. 3 Respiration Vol. II. Chapter 36. Baltimore: Williams & Wilkins Co., 1965.

3. Aostrand, P. O., and B. Saltin. "Oxygen Uptake During the First Minutes of Heavy Muscular Exercise." J. Appl. Physiol., 16: 971-976, 1961.

4. Banerjee, S., A. Barua, and A. Ghosh. "Energy Metabolism in College Girls." J. Appl. Physiol., 16:164, 1961.

5. Bannister, R. C., and D. J. C. Cunningham. "The Effect on the Respiration and Performance During Exercise of Adding Oxygen to the Inspired Air." J. Physiol., 125:118, 1954.

6. "Baralyme Granules - Carbon Dioxide Gas Absorbent." Bulletin NM-151.300 by National Cylinder Gas.

7. Bedford, T. "Research on Heating and Ventilation in Relation to Human Comfort." ASHRAE Transactions, 65:83, 1959.

8. Benedict, F. G., and E. P. Cathcart. Musuclar Work. Washington: Carnegie Institution, 1913.

9. Benedict, F. G., and H. S. Parmenter. "The Energy Metabolism of Women While Ascending or Descending Stairs." Am. J. Physiol., 84:675, 1928.

10. Best, C. H., and N. B. Taylor. "General Metabolism." The Physiological Basis of Medical Practice., 6th ed. Baltimore: Williams and Wilkins Co., 1955.

11. Booyens, J., and W. R. Keatinge. "Energy Expenditure During Walking." J. Physiol., 138:165, 1957.

12. Boudreau, M. W. and R. K. Pefley. "Monoman Calorimeter Study as it Relates to Considerations of the Non-Isostate Aspect of Civil Defense Shelters." ASHRAE Transactions, 1967 (in press).

13. Brouha, L., P. E. Smith, R. DeLanne, and Mary E. Maxfield. "Physiological Reactions of Men and Women During Muscular Activity and Recovery in Various Environments." J. Appl. Physiol., 16:133-140, 1961.

14. Brouha, L., Mary E. Maxfield, P. E. Smith, Jr., and G. J. Stoppts. "Discrepancy Between Heart Rate and Oxygen Consumption During Work in the Warmth." J. Appl. Physiol., 18:1095-1098, 1963.

15. Brown, E. S. "Factors Affecting the Performance of Absorbents." Anesthesiology, 20:198-203, 1959.

16. Brown, E. S., V. Bakamjian, and A. M. Seniff. "Performance of Absorbents: Effect of Moisture." Anesthesiology, 20:613-617, 1959.

17. Brown, E. S. "Voids, Pores, and Total Air Space of Carbon Dioxide Absorbents." Anesthesiology, 19:1-6, 1958.

18. Buettner, K. J. K., and F. F. Holmes. "Diffusion of Water Vapor through Human Skin in Hot Environment and with Application of Atropine." J. Appl. Physiol., 14:276-278, 1959.

19. Buettner, K. J. K. "Diffusion of Water Vapor Through Human Skin." J. Appl. Physiol., 14:261-268, 1959.

20. Burton, A. C., and O. G. Edholm. Man in a Cold Environment. London: Edward Arnold Publishers Ltd., 1955.

21. Campbell, E. J. M., E. K. Westlake, and R. M. Cherniack. "Simple Methods of Estimating Oxygen Consumption and Efficiency of the Muscles of Breathing." J. Appl. Physiol., 11:303-308, 1957.

22. Carrier, W. H. "The Control of Humidity and Temperatures as Applied to Manufacturing Processes and Human Comfort." ASHVE Paper No. 324.

23. Consolazio, C. F., L. R. D. Matoush, R. A. Nelson, J. B. Torres, and G. J. Isaac. "Environmental Temperature and Energy Expenditures." J. Appl. Physiol., 18:65-68, 1963.

24. Craig, F. N., E. G. Cummings, and W. V. Blevins. "Regulation of Breathing at Beginning of Exercise." J. Appl. Physiol., 18:1183, 1963.

25. Dill, D. B., and C. F. Consolazio. "Responses to Exercise as Related to Age and Environmental Temperature." J. Appl. Physiol., 17:645, 1962.

26. DuBois, E. F. Basal Metabolism in Health and Disease. Philadelphia: Lea and Febiger, 1936.

27. DuBois, E. F. Fever and the Regulation of Body Temperature. Springfield, Illinois: Charles C. Thomas, 1948.

28. Edholm, O. G., J. M. Adam, and R. H. Fox. "The Effects of Work in Cool and Hot Conditions on Pulse Rate and Body Temperature." Ergonomics, 5:545-556, 1962.

29. Elbel, E. R., D. Ormond, and D. Close. "Some Effects of Breathing Oxygen Before and After Exercise." J. Appl. Physiol., 16:48-52, 1961.

30. Fahnestock, M. K., F. E. Boys, F. Sargent II, and L. D. Siler. "Energy Costs, Comfort and Physiological Responses to Physical Work in 95F-50% RH and 75F-45% RH Environments." ASHRAE Transactions, 1967 (in press).

31. Fahnestock, M. K., F. E. Boys, F. Sargent II, W. E. Springer, and L. D. Siler. "Comfort and Physiological Responses to Work in an Environment of 75F and 45% Relative Humidity." ASHRAE Transactions, 69:13-23, 1963.

32. Fahnestock, M. K. and J. E. Werden. "Environment Comfort, Health and People." Refrigerating Engineering, February 1956, 64:43-49.

33. Fanger, P. O. "Calculation of Thermal Comfort: Introduction of a Basic Comfort Equation." ASHRAE Transactions, 1967 (in press).

34. Ford, A. B., and H. K. Hellerstein. "Energy Cost of the Master Two-Step Test." Journal of American Medical Association, 164:1868-1874, 1957.

35. Gagge, A. P. "Comfort: New Concepts and Applications." Building Research, July-August 1966, 15-22.

36. Gagge, A. P., C.-E. A. Winslow and L. P. Herrington. "The Influence of Clothing on the Physiological Reactions of the Human Body to Varying Environmental Temperatures.", Am. J. Physiology, 124:30-50, 1938.

37. Guibert, A., and C. L. Taylor. "Radiation Area of the Human Body." J. Appl. Physiol., 5:24-37, 1952.

38. Hale, F. C., R. A. Westland, C. L. Taylor. "Barometric and Vapor Pressure Influences on Insensible Weight Loss." J. Appl. Physiol., 12:20-28, 1958.

39. Hall, Jr., J. F., and F. K. Klemm. "Insensible Weight Loss of Clothed Resting Subjects in Comfort Zone Temperatures." J. Appl. Physiol., 18:1188-1192, 1963.

40. Hardy, J. D., and A. T. Milhorat. "Basal Heat Loss and Production in Women at Temperatures from 23-36°C." Proc. Soc. Exper. Biol. and Med. 41:94-98, 1939.

41. Hardy, J. D., and E. F. DuBois. "Difference Between Men and Women in the Response to Heat and Cold." Proceedings National Academy of Science, 26:389-398, 1940.

42. Hardy, J. D., and E. F. DuBois. "The Technique of Measuring Radiation and Convection." J. Nutr., 15:461, 1938.

43. Hardy, J. D. "Physiology of Temperature Regulation." Physiol. Rev., 41:521-606, 1961.

44. Harmon, F. L. "Reliability of Metabolism Measurements by the Closed Circuit Method." J. Appl. Physiol., 5:773-778, 1953.

45. Hellebrandt, F. A., E. Brogdon, and R. Tepper. "Posture and Its Cost." Am. J. Physiol., 129:773, 1940.

46. Henry, F. M. and H. R. Fitzhenry. "Oxygen Metabolism of Moderate Exercise with Some Observations on the Effects of Tobacco Smoking." J. Appl. Physiol., 2:464, 1950.

47. Hertzman, A. B., W. C. Randall, C. N. Peiss, and R. Seckendorf. "Regional Rates of Evaporation from the Skin at Various Environmental Temperatures." J. Appl. Physiol. 5:153-161, 1952.

48. Hick, F. K., T. Inouye, R. W. Keeton, M.D., N. Glickman, and M. K. Fahnestock. "Physiological Adjustments of Clothed Human Beings to Sudden Change in Environment - First Moist and Later Comfortable Conditions." ASHVE Transactions, 58:189-190, 1952.

49. Hickish, D. E. "Thermal Sensations of Workers in Light Industry in Summer: A Field Study in Southern England." J. Hyg., Cambridge, 53:112-123, 1955.

50. Houghton, F. C., and C. Gutberlet. "Comfort Standards for Summer Air Conditioning." ASHVE Transactions, 42:215-259, 1936.

51. Houghton, F. C., and C. P. Yaglou. "Determination of Comfort Zone." ASHVE Transactions, 29:361-384, 1923.

52. Houghton, F. C., and C. P. Yaglou. "Determining Lines of Equal Comfort." ASHVE Transactions, 29:163-176, 1923.

53. Houghten, F. C. "Progress in Development of Standards for Comfort Air Conditioning." ASHVE Transactions, 50:87-98, 1944.

54. Houghton, F. C., W. W. Teague, W. E. Miller and W. P. Yant. "Heat and Moisture Losses from Men at Work and Applications to Air Conditioning Problems." ASHVE Transactions, 37:541-570, 1931.

55. Houghton, F. C., W. W. Teague, W. E. Miller, and W. P. Yant. "Thermal Exchanges Between the Bodies of Men Working and the Atmospheric Environment." Am. Journal of Hyg., 13:415-431, 1931.

56. Humpheys, C. M., A. F. Henschel, and D. H. K. Lee. "Sensible and Latent Heat Losses from Occupants of Survival Shelters." ASHRAE Transactions, 72:255-263, 1966.

57. Iampietro, P. F., D. E. Bass, and E. R. Buskirk. "Heat Exchanges of Nude Men in the Cold: Effect of Humidity, Temperature and Windspeed." J. Appl. Physiol., 12:351-356, 1958.

58. Iampietro, P. F., E. R. Buskirk, and J. A. Vaughan. "Effects of High and Low Humidity on Heat Exchanges of Lightly Clothed Men." J. Appl. Physiol., 15:212-214, 1960.

59. Inouye, T., F. K. Hick, M.D., R. W. Keeton, M.D., J. Losch, and N. Glickman. "A Comparison of Physiological Adjustments of Clothed Women and Men to Sudden Changes in Environment." ASHVE Transactions, 59:35-48, 1953.

60. Inouye, T., F. K. Hick, S. E. Tesler, and R. W. Keeton. "Effect of Relative Humidity on Heat Loss of Men Exposed to Environments of 80, 76, and 72F." ASHVE Transactions, 59:329-346, 1953.

61. Issekute, B., and K. Rodahl. "Respiratory Quotient During Exercise." J. Appl. Physiol., 16:606-610, 1961.

62. Jacob, M., and G. A. Hawkins. Elements of Heat Transfer. New York: John Wiley and Sons, Inc., 1961.

63. Jennings, B. H., and B. Givoni. "Environment Reactions in the 80F to 105F Zone." ASHRAE Transactions, 65:115-136, 1959.

64. Karpovich, P. V. Physiology of Muscular Activity. Philadelphia: W. B. Saunders Co., 1965.

65. Keeton, R., M.D., F. K. Hick, M.D., N. Glickman, and M. M. Montgomery, M.D. "The Influence of Physiological Research on Comfort Requirements." ASHVE Transactions, 47:159-174, 1941.

66. Kleiber, M. "Physiological Meaning of Regression Equations." J. Appl. Physiol., 2:417-423, 1949.

67. Kleiber, M. "Respiratory Exchange and Metabolic Rate." Handbook of Physiology Sect. 3 Respiration Vol. II. Chapter 35. Baltimore: Williams and Wilkins Co., 1965.

68. Kleiber, M. The Fire of Life. New York: John Wiley and Sons, Inc., 1961.

69. Knuttgen, H. G. "Oxygen Debt, Lactate, Pyruvate, and Excess Lactate After Muscular Work." J. Appl. Physiol., 17:639, 1962.

70. Koch, W., B. H. Jennings, and C. M. Humphreys. "Environmental Study II - Sensation Responses to Temperature and Humidity Under Still Air Conditions in the Comfort Range." ASHRAE Transactions, 66:264-287, 1960.

71. Kranz, P. "Calculating Human Comfort." ASHRAE Journal, 6:68-77, 1964.

72. Lambert, G. E. "Work, Sleep, Comfort." Environmental Physiology and Psychology in Acid Conditions. New York: United Nations Educational, Scientific and Cultural Organization, 1963.

73. Leopold, C. S. "Engineering Aspects of Comfort Data." Heating, Piping and Air Conditioning, 23:136, 1951.

74. Mahadeva, K., R. Passmore, and B. Woolf. "Individual Variations in Metabolic Cost of Standardized Exercises: Effects of Food, Age, Sex, and Race." J. Physiol., 121:225, 1953.

75. Malhotra, M. S., S. S. Ramaswamy, and S. N. Ray. "Effect of Environmental Temperature on Work and Resting Metabolism." J. Appl. Physiol., 15:769-770, 1960.

76. Master, A. M. "Two-Step Exercise Electrocardiogram: Test for Coronary Insufficiency." Ann. Internal Med., 32:842-863, 1950.

77. McConnell, W. J., and C. P. Yaglou. "Work Tests Conducted in Atmospheres of Low Temperatures in Still and Moving Air." ASHVE Transactions, 32: 237-248, 1926.

78. McConnell, W. J., C. P. Yaglou, and W. B. Fulton. "Basal Metabolism Before and After Exposure to High Temperatures and Various Humidities." ASHVE Transactions, 31:1925.

79. McCormick, H. G. The Metabolic Cost of Maintaining a Standing Position. New York: King's Crown Press, 1942.

80. McDonald, I. "Statistical Studies of Recorded Energy Expenditure of Man." Nutr. Abstr. and Rev., 31:739-761, 1961.

81. McNall, Jr., P. E., J. Jaax, F. H. Rohles, R. G. Nevins, and W. Springer. "Thermal Comfort (Thermally Neutral) Conditions for Three Levels of Activity." ASHRAE Transactions, 1967 (in press).

82. McNall, Jr., P. E., and D. J. Sutton. "Thermal Comfort and Comfort Equations for Heating Applications." GR 1823-R2, Minneapolis-Honeywell Regulator Company Research Report, Minneapolis, Minnesota, July 1953.

83. Miura, U. "The Effect of Variation in Relative Humidity Upon Skin Temperature and Sense of Comfort." Am. J. Hyg., 13:432-459, 1931.

84. Morehouse, L. E., and A. T. Miller. Physiology of Exercise. St. Louis: The C. V. Mosby Co., 1948.

85. Nevins, R. G. "Criteria for Thermal Comfort." Building Research, July-August 1966, 27-30.

86. Nevins, R. G. and J. D. Hardy. "Humidity Effects on the Comfort and Well-Being of People." Paper at 1963 International Symposium on Humidity and Moisture, May 20-23, 1963.

87. Nevins, R. G., F. H. Rohles, W. Springer, and A. M. Feyerherm. "A Temperature Humidity Chart for Thermal Comfort of Seated Persons." ASHRAE Journal, April 1966, 8:55-62.

88. Owens, B. W., and G. Latta. "On the Measurement of Human Power." The Trend in Engineering, 18(1):21-27, 1966.

89. Passmore, R., and J. V. G. A. Durnin. "Human Energy Expenditure." Physiological Review, 35:801-840, 1955.

90. Robinson, S. "The Effect of Body Size Upon Energy Exchange in Work." Am. J. Physiol., 136:363-368, 1942.

91. Rohles, F. H. "Consideration for Environmental Research in Human Factors." Journal of Environmental Sciences, 8(3):18-20, 1965.

92. Seltzer, C. C. "Body Build and Oxygen Metabolism at Rest and During Exercise." Am. J. Physiol., 129:1-13, 1940.

93. Snedecor, G. W. Statistical Methods. Ames, Iowa: Iowa State University Press, 1961.

94. Suggs, C. W., and W. E. Splinter. "Some Physiological Responses of Man to Workload and Environment." J. Appl. Physiol., 16:413-420, 1961.

95. Swift, R. W., and F. H. Fisher. "Energy Metabolism." Nutrition, Chapter IV. New York: Academic Press, 1964.

96. Tanner, J. M. "Fallacy of Per-Weight and Per-Surface Area Standards, and Their Relation to Spurious Correlation." J. Appl. Physiol., 2:1-15, 1949.

97. Tasker, C., C. M. Humphreys, G. V. Parmelee, and L. F. Shutram. "The ASHVE Environmental Laboratory. ASHVE Transactions, 58:139-154, 1952.

98. Taylor, C. "Studies in Exercise Physiology." Am. J. Physiol., 135:27-42, 1941.

99. Taylor, H. L. "Exercise and Metabolism." Science and Medicine of Exercise and Sports, Chapter 8. New York: Harper and Row, 1960.

100. "Thermal Comfort conditions." ASHRAE Standard 55-66, January 27, 1966.

101. Webb, P. "Dissociation of Heat Production and Heat Loss in Working Men." American Society of Mechanical Engineers publication 66-WA/HT-45.

102. Webb, P. "Energy Costs." Bioastronautics Data Book, Chapter 10. Washington: Government Printing Office, 1964.

103. Webb, P., L. N. Garlington, and M. J. Schwarz. "Insensible Weight Loss at High Skin Temperatures." J. Appl. Physiol., 11:41-44, 1957.

104. Welles, J. G., B. Balke, and D. D. Van Fossan. "Lactic Acid Accumulation During Work." J. Appl. Physiol., 10:51, 1957.

105. White, A., P. Handler, and E. L. Smith. Principals of Biochemistry. New York: McGraw-Hill, 1964, 292.

106. Williams, C. G., G. A. G. Bredell. C. H. Wyndham. N. B. Strydom, J. F. Morrison, J. Peter, P. W. Fleming, and J. S. Ward. "Regulatory and Metabolic Reactions to Work in Heat." J. Appl. Physiol. 17:625-638, 1962.

107. Winslow, C.-E. A., and L. P. Herrington. Temperature and Human Life. Princeton: Princeton University Press, 1949.

108. Winslow, C.-E. A., A. P. Gagge, and L. P. Herrington. "The Influence of Air Movement upon Heat Losses from the Clothed Human Body." Am. J. Physiol., 127:505-518, 1939.

109. Winslow, C.-E. A., L. P. Herrington, and A. P. Gagge. "Physiological Reactions of the Human Body to Various Atmospheric Humidities." Am. J. Physiol., 120:288-299, 1937.

110. Winslow, C.-E. A., L. P. Herrington, and A. P. Gagge. "Physiological Reactions of the Human Body to Varying Environmental Temperatures." Am. J. Physiol., 120:1-22, 1937.

111. Winslow, C.-E. A., L. P. Herrington, and A. P. Gagge. "The Relative Influence of Radiation and Convection upon the Temperature Regulation of the Clothed Body." Am. J. Physiol., 124:51-61, 1938.

112. Wortz, E. C., and E. J. Prescott. "Effects of Subgravity Traction Simulation on the Energy Costs of Walking." Aerospace Medicine, 37:1217-1222, 1966.

113. Wyndham, C. H., N. B. Strydom, J. F. Morrison, C. G. Williams, G. Bredell, J. Peter, H. M. Cooke, and A. Joffe. "The Influence of Gross Body Weight on Oxygen Consumption and on Physical Working Capacity of Manual Labourers." Ergonomics, 6:275-286, 1963.

114. Yaglou, C. P. and P. Drinker. "Summer Comfort Zone, Climate and Clothing." ASHVE Transactions, 35:269-286, 1929.

APPENDICES

APPENDIX A

Indoctrination Information Given Orally to the Sedentary Test Subjects

The purpose of this test is to determine your metabolic rate while sitting quietly. This will be done by measuring the amount of pure medical oxygen you consume over an eight minute period. As soon as preparations are completed in the pre-test room, we will take you into the test room next door in staggered intervals of ten minutes. You will take a chair and be seated. You can read, study, or converse as long as you remain relatively quiet. During the first hour the nurse will show you how to put on the nose clips and let you familiarize yourself with a sterilized mouthpiece. At the end of your first, second and third hours in the test room you will breath oxygen through the metabulator for eight minutes and from this we will later determine your metabolic rate.

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

Are there any questions?

APPENDIX B

Indoctrination Information Given Orally to the Activity Test Subjects

The purpose of this test is to determine your metabolic rate while engaged in various activities. This will be done by measuring the amount of pure medical oxygen you consume while walking over a two step block for five minutes. The length of the standing time will be different for each of the three days you participate. Here is a time flow sheet telling each subject what he or she is to be doing at a given time for the three hour test period. The nurse will assist you in following this flow sheet.

As soon as preparations are completed in the pre-test room, we will then take you into the test room next door in staggered intervals of twenty minutes. Upon entering the test room you will immediately begin walking over the steps. Take one step at each "click" of enunciator and use one "click" to turn around on at the end of the step. You will walk for five minutes and then take a place at the table until it is time to walk again. While you are in the room you may play cards, study or engage in quiet conversation.

During one of the standing periods of the first hour the nurse will show you how to put on the nose clips and let you familiarize yourself with a sterilized mouthpiece. At the end of your first, second and third hours in the test room you will breath oxygen during the one walk and stand period and from this we will later determine your metabolic rate.

All persons participating in these tests will sign a receipt for your pay of $15.00 which will be given to you at the end of the third day test period.

Are there any questions?

APPENDIX C

Analysis of Air Motion Over Subjects Engaged in Three Levels of Activity

Measurements from moving pictures of typical male and female subjects indicated that the average subject moved 9 in/sec vertically and 11.25 in/sec horizontally while walking over the steps. This resulted in a velocity vector of 14.4 in/sec or 72 ft/min. A previous analysis of the air motion within the test chamber in the vicinity of the subjects indicated that the rate of air movement was approximately 30 ft/min. Assuming the two motions to be additive, the resulting air movement rate while walking would be 102 ft/min and 30 ft/min while standing. Therefore, for the three activity cycles the resulting average air movements would be:

High activity level; Average Velocity = 1/2(102) + 1/2(30) = 66 ft/min

Medium activity level; Average Velocity = 1/3(102) + 2/3(30) = 54 ft/min

Low activity level; Average Velocity = 1/6(102) + 5/6(30) = 45 ft/min

APPENDIX D

Data sheets for recording physiological data and controlling the subjects' activities.

Project No.__________

Test No.__________

Date__________

DB_____RH_____WB_____

Activity

Walk________Min.

Stand_______Min.

Subjects Name	Age	Oral Temperature	Height	Initial Weight (clothed) lb	Final Weight (clothed) lb	Weight Difference	Water (initial) cc	Water (final) cc	Difference cc	Pulse (Beats/min) in/out	REMARKS

Figure D-1. Height, weight, heart rate, oral temperature, and age record sheet.

Flow Sheet - Metabolic Activity Studies
1966

Time	Subject #1			Subject #2			Subject #3		
	10 min cycle	15 min cycle	30 min cycle	10 min cycle	15 min cycle	30 min cycle	10 min cycle	15 min cycle	30 min cycyle
1300 or									
1800	WALK	WALK	W						
05	STAND	STAND	S						
10	W	S	S						
15	S	W	S						
20	W	S	S	W	W	W			
25	S	S	S	S	S	S			
30	W	W	W	W	S	S			
35	S	S	S	S	W	S			
40	W	S	S	W	S	S	W	W	W
45	S	W	S	S	S	S	S	S	S
50	W	S	S	W	W	W	W	S	S
55	S	S	S	S	S	S	S	W	S
1400 or	*								
1900	W	W	W	W	S	S	W	S	S
05	S	S	S	S	W	S	S	S	S
10	W	S	S	W	S	S	W	W	W
15	S	W	S	S	S	S	S	S	S
20	W	S	W	W	W	W	W	S	S
25	S	S	S	S	S	S	S	W	S
30	W	W	W	W	S	S	W	S	S
35	S	S	S	S	W	S	S	S	S
40	W	S	S	W	S	S	W	W	W
45	S	W	S	S	S	S	S	S	S
50	W	S	S	W	W	W	W	S	S
55	S	S	S	S	S	S	S	W	S
1500 or									
2000	W	W	W	W	S	S	W	S	S
05	S	S	S	S	W	S	S	S	S
10	W	S	S	W	S	S	W	W	W
15	S	W	S	S	S	S	S	S	S
20	W	S	S	W	W	W	W	S	S
25	S	S	S	S	S	S	S	W	S
30	W	W	W	W	S	S	W	S	S
35	S	S	S	S	W	S	S	S	S
40	W	S	S	W	S	S	W	W	W
45	S	W	S	S	S	S	S	S	S
50	W	S	S	W	W	W	W	S	S
55	S	S	S	S	S	S	S	W	S
1600 or									
2100	W	W	W	W	S	S	W	S	S
05	S	S	S	S	W	S	S	S	S
10	W	S	S	W	S	S	W	W	W
15				S	S	S	S	S	S
20		OUT		W	W	W	W	S	S
25				S	S	S	S	W	S
30				W	S	S	W	S	S
35							S	S	S
40					OUT		W	W	W
45							S	S	S
50							W	S	S
55								OUT	

* Heavy lines indicate where subjects metabolic rate is to be measured

Figure D-2. Flow sheet for the high, medium and low levels of activity.

APPENDIX E

Suggestions on Indirect Closed-Circuit Calorimetry

During the preliminary testing of the low, medium and high activity levels, a metal absorbent cannister was used to remove the carbon dioxide in the exhaled air. This system was not as nearly free flowing as the clear plastic cannister shown in Figure 2. Laboratory personnel reported that the metal cannister caused labored breathing and was abandoned in favor of the free-flowing, low-resistance cannister. A well designed cannister should have a header so that the expired gases are evenly distributed throughout the cannister and should be large enough to allow sufficient time for the CO_2 to be absorbed. Proper packing of the cannister is also essential; therefore, a removable, full-size top is necessary. While channeling of the gases may be a problem, proper packing and baffling will correct this. A cannister of clear plastic was the most practical, as it permitted visual observation of the color changes inherent in indicating soda-lime as it absorbs carbon dioxide. This is important, because the absorbent will revert to its original color if it is allowed to stand unused for several hours and will only return to its former color level one hour or more after the absorbent's next usage (6). The expired gas should enter the top of the cannister and exit at the bottom. This forces the water liberated in the chemical reaction of the absorption to the bottom of the cannister, and, consequently, the liberated water does not hinder the color change. Moisture, however, does not affect the absorption characteristics of soda-lime (16). The life of the absorbent is inversely proportional to the carbon dioxide input rate in a cannister of adequate dimensions (15).

It is essential in metabolic measurements that one exercise extreme care, as the sources of error are plentiful. In reviewing the literature and experimentation by the author, the following suggestions and points are offered. This list is by no means meant to be all-inclusive.

1. The system should constantly be checked for leaks. Without a doubt, they are the biggest source of erroneous data (95).
2. The system should be matched to the type, magnitude, and duration of the experiment.
3. The system should be checked often to insure that it is free-flowing and offering little or no resistance to breathing. (A problem we encountered was the overflowing of water into the breathing pipes of the gasometer).
4. The entire system should be accurately calibrated at the beginning and at the conclusion of the experiment.
5. The subjects should be orientated and familiar with the nature of the experiment and should be permitted to familiarize themselves with the mouthpiece and breathing valve prior to taking any data.
6. The equipment in contact with the oxygen should be kept clean and sterile.
7. The absorption cannister should be of the proper size and design, and the absorbent should be changed when it is approximately half exhausted in order to prevent incomplete absorption of carbon dioxide.

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HEAT PRODUCTION OF COLLEGE-AGE PERSONS AT FOUR LEVELS OF ACTIVITY AND THEIR CORRESPONDING THERMAL COMFORT CONDITIONS

by

PATRICK WILLIAM RYAN

B. S., Kansas State University, 1964

AN ABSTRACT OF A THESIS

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KANSAS STATE UNIVERSITY
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ABSTRACT

A study was conducted to determine human metabolic rates at four levels of activity and then correlate these results with thermal comfort. In addition heart rate and evaporative heat loss were analyzed. Using college-age males and females the following levels of activity were examined: sedentary, in which the subjects sat quietly at tables; low activity, which consisted of performing a modified step test for 5-minutes and standing for 25-minutes; medium activity, in which the step test was performed for 5-minutes and standing for 10-minutes; high activity, in which the step test was performed for 5-minutes and standing for 5-minutes. Thirty subjects were employed at the sedentary activity level at one of three environmental temperatures; 66, 72, or 78 F, all at 50% RH. In addition, ten similar subjects were used at the low, medium and high activity levels at 72, 66, and 60 F respectively, all at 45% RH. These environments had previously been found to be thermally neutral for the respective activity levels. The test period duration was always three hours.

The results showed that: (1) Sedentary metabolic rate was independent of the environmental temperature over the range 66 to 78 F; (2) The third-hour sedentary metabolic rates for all three temperatures were 389 and 301 Btu/hr for the males and females respectively; (3) The metabolic rate normalized for clothed body weight while walking in the low, medium and high activity levels was the only metabolic rate not related to the sex of the subject; (4) The third-hour metabolic rates for the low, medium, and high levels of activity were 622, 829, and 1061 Btu/hr, respectively, for the males and 492, 653 and 826 Btu/hr,

respectively, for the females; (5) The metabolic rates were correlated with thermal comfort conditions reported by previous investigators for the same activities and a proposed thermal comfort zone as a function of metabolic rate was presented; (6) The percent of evaporative heat loss of the total heat production for the low, medium and high activity levels was independent of sex and the activity level and, hence, this variable might be an index of thermal comfort; (7) A comparison between measured heat production and calculated heat loss was presented; (8) Equations determined from a regression analysis for predicting metabolic rates for sedentary, standing and walking subjects based on their height and weight were presented and the results indicated that the subjects weight was the principal variable governing walking and standing metabolic rates and evaporative heat loss.

VITA

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