FIGURE 3.2

The important components of the controller.

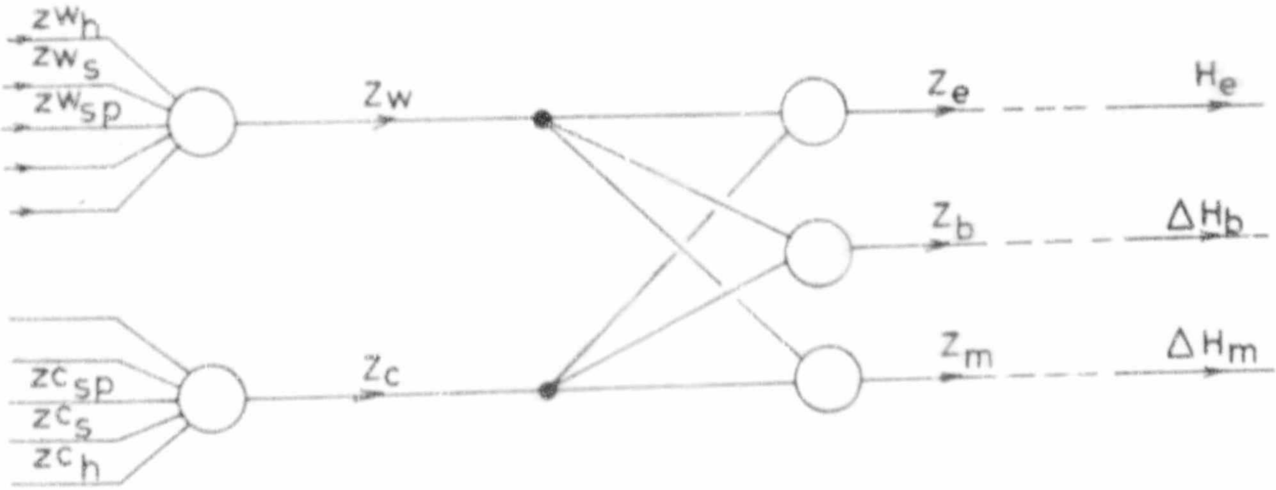

FIGURE 3.3

A simple model of the neuro-integrating centre of the controller.

and

$$Z_c = \Sigma(zc)_h + \Sigma(zw)_s + \Sigma(zw)_{sp} + \ldots \quad 3\text{-}5$$

where $(zw)_h$ and $(zc)_h$ are the warm and cold sensors in the hypothalamus, respectively

$(zw)_s$ and $(zc)_s$ are the warm and cold sensors in the skin respectively, and,

$(zw)_{sp}$ and $(zc)_{sp}$ are the warm and cold sensors in the spine respectively.

The warm and cold 'signals' combine to form the three control action 'driving signals', Z_e, Z_b, and Z_m which in turn initiate the control actions.

The sweat control signal is used to prevent the development of a heat stress and therefore responds only to warm signals. The warm signal may be inhibited totally or partially by the cold signal. The metabolic term is used to prevent the development of a cold stress and responds only to a cold signal. The cold signal is similarly inhibited by the warm signal.

The peripheral blood-flow control action responds to both warm and cold causing vasodilation or vasoconstriction, respectively. The driving signal Z_b is assumed to be an interaction of both warm and cold signals. In order to simplify mathematical analysis, the cold sensors are given negative signs so that

$$Z_b = Z_w - Z_c \quad 3\text{-}6$$

or

$$Z_b = (zw)_h + (zw)_s + (zw)_{sp} + \ldots - (zc)_h - (zc)_s - (zc)_{sp} - \ldots \quad 3\text{-}7$$

If the temperature characteristics of the control action are required, the components of equation 3-7 must be grouped in pairs according to their source references, that is, the hypothalamus, the skin and the spine. Therefore

$$z_b = ((zw)_h - (zc)_h) + ((zw)_s - (zc)_s) + ((zw)_{sp} - (zc)_{sp}) + . \quad 3\text{-}8$$

$$= z_h + z_s + z_{sp} + \ldots \quad 3\text{-}9$$

where z_h, z_s and z_{sp} are the resultant signals from the hypothalamus, skin and spine respectively.

The combined neuro-temperature characteristic of either component, for example the hypothalamus, will have the form illustrated in Figure 3.4A. The resultant solid line is made up of typical warm and cold neuro-temperature sensor characteristics, represented by the broken lines. The resultant curve may be represented as a first approximation, by a straight line over a limited range of temperature. That is,

$$z_h = k_h(T_h - T_h') \quad 3\text{-}10$$

where k_h is the slope of the line and
T_h' is the intercept.

Therefore

$$z_b = k_h(T_h - T_h') + k_s(T_s - T_s') + k_{sp}(T_{sp} - T_{sp}') + \ldots \quad 3\text{-}11$$

The final driving signal is therefore the sum of the resultant 'signals' from the various zones of the body. Experimental evidence suggests that the skin neuro-sensors are sensitive to both a proportional and a rate of change of skin temperature, and there is a modulation term caused by the neuro-motor control being temperature sensitive.

The complete 'driving signal' may therefore be represented by

$$z_b = k_m T_s [k_h(T_h - T_h') + k_s(T_s - T_s') + k_{ds} dT_s/dt + k_{sp}(T_{sp} - T_{sp}') + \ldots] \quad 3\text{-}12$$

where k_{sn} is a constant representing thermal sensitivity of the neuro-motor control, and

k_{ds} is a constant representing the thermal sensitivity of the rate of change of skin temperature.

The driving signals for evaporation and metabolism may be represented in a similar manner, with two exceptions:

a) a negative value of Z_e will represent a predominantly cold signal with the result that the evaporation H_e will be zero;

b) a positive value of Z_m will represent a predominantly warm signal with the result that ΔH_m is zero. (Refer to Figures 3.4B and 3.4C)

It is important to note that the threshold temperature forms part of the linear expression which is assumed to relate a control action with temperature. This does not imply, however, that there is a reference temperature source. Figure 3.5 illustrates the difference between a control system with a reference source and a control system with opposing feedback sources. Physically they are different though analytically they are similar.

In order to understand the controller characteristics it is necessary to evaluate the equation 3-12. If the characteristics are non-linear then the coefficients, $k_{(\ )}$, will vary with body temperature.

There is no evidence and no reason to suppose that the controller has a significant time lag. For this reason it is ignored.

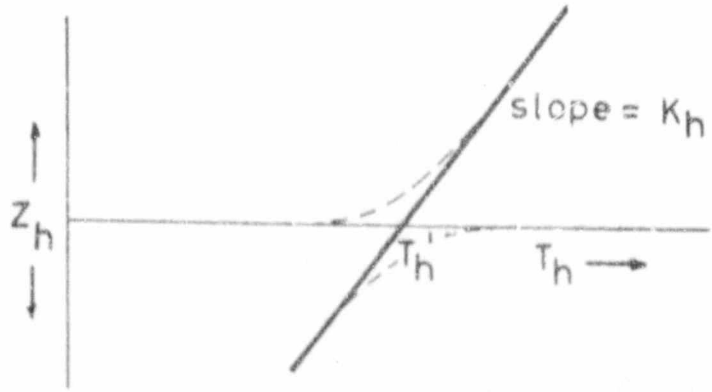

FIGURE 3.4A

The temperature characteristics of the hypothalamic component of peripheral blood flow control.

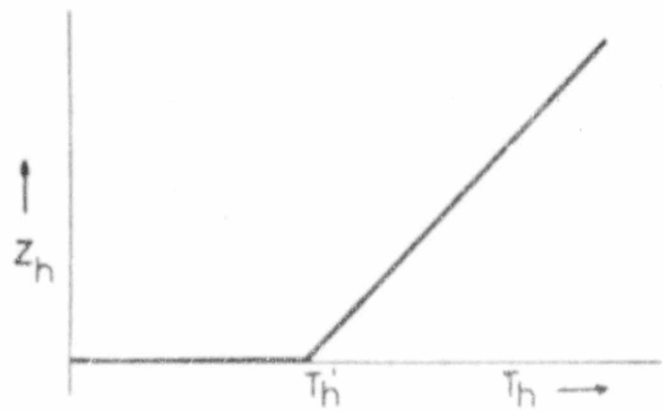

FIGURE 3.4B

The temperature characteristics of the hypothalamic component of sweat rate control.

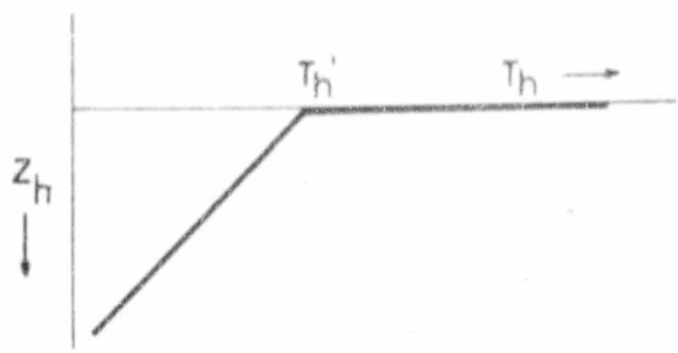

FIGURE 3.4C

The temperature characteristics of the hypothalamic component of metabolic heat control.

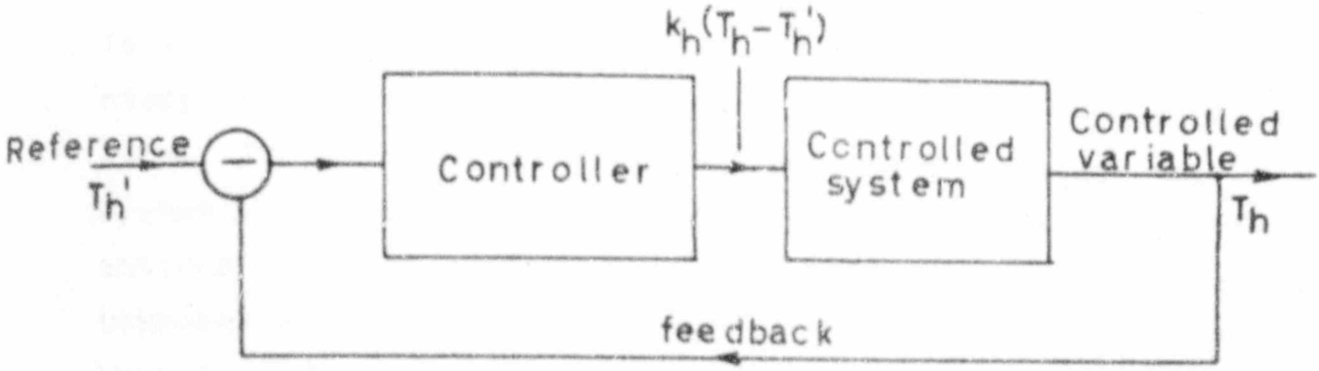

FIGURE 3.5A

A controller using a reference signal to determine the magnitude of the control variable.

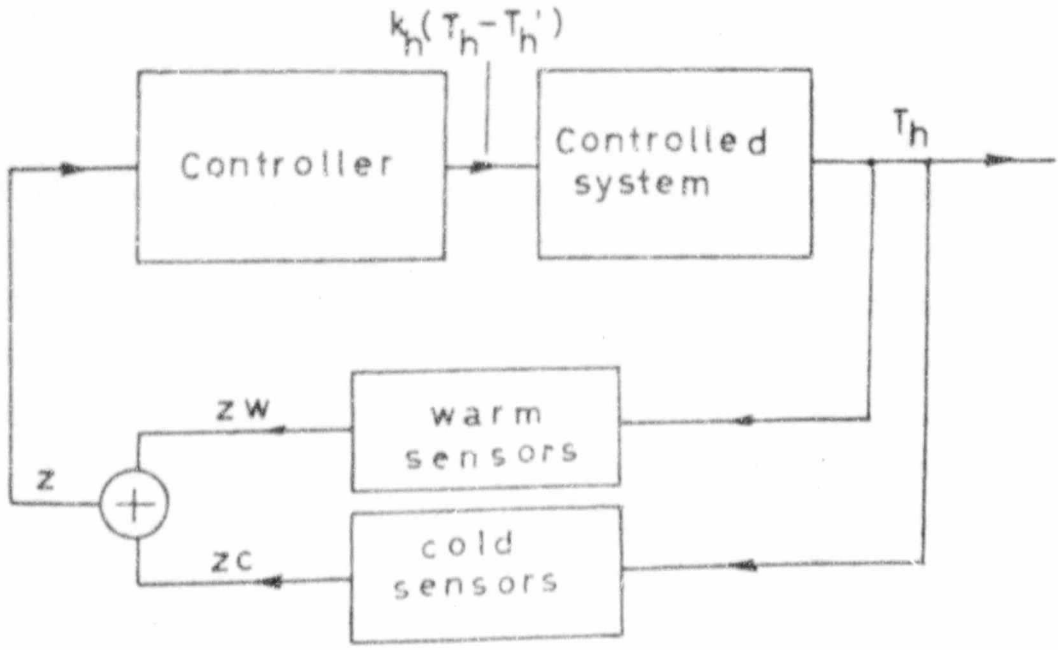

FIGURE 3.5B

A controller using the interaction of two opposing feedback signals to determine the magnitude of the control variable.

3.4 The controlled system

3.4.1 Thermal properties and metabolic heat input

The object of the investigation described in this thesis is a study of body temperature control and not a detailed study of heat flow or temperature distribution throughout the body. For this reason it is not necessary to study the controlled system in detail; a simple model which relates the control actions with the control variables will suffice. The body is represented by a single cylinder in which there are only radial heat transfer and radial thermal gradients. The surface temperature of the cylinder represents the mean skin temperature. A cylindrical model differs slightly from a semi-infinite slab model in that the thermal parameters of a cylinder are functions of radius whereas a slabs parameters are independent of geometry.

The model is illustrated in Figure 3.6. It comprises four concentric sections, the core, the muscle, the fatty tissue and the skin. The core includes the skeleton, all organs with the exception of those associated directly with the circulatory system and deep tissue surrounding the organs. The muscle includes all muscle of the trunk and the limbs. Tissue represents the layer of fatty tissue between the muscle and the skin. The tissue varies in depth at different parts of the body, but this is of little consequence since the model represents average body dimensions. The skin includes both the dermis, which contains the peripheral capillary blood vessels, and the epidermis which has no blood vessels. The circulatory system including the central blood pool of the heart and lungs is treated separately.

The core, muscle and tissue are assumed to be homogenous, that is, the conductivity, capacity, the rate of heat production due to metabolism and the rate of heat exchange with the blood stream are uniform in each zone. The skin is examined in futher detail below. The thermal properties of the cylinder, listed in Table 3.1, are taken from measurements of a typical man (Atkins, 1968).

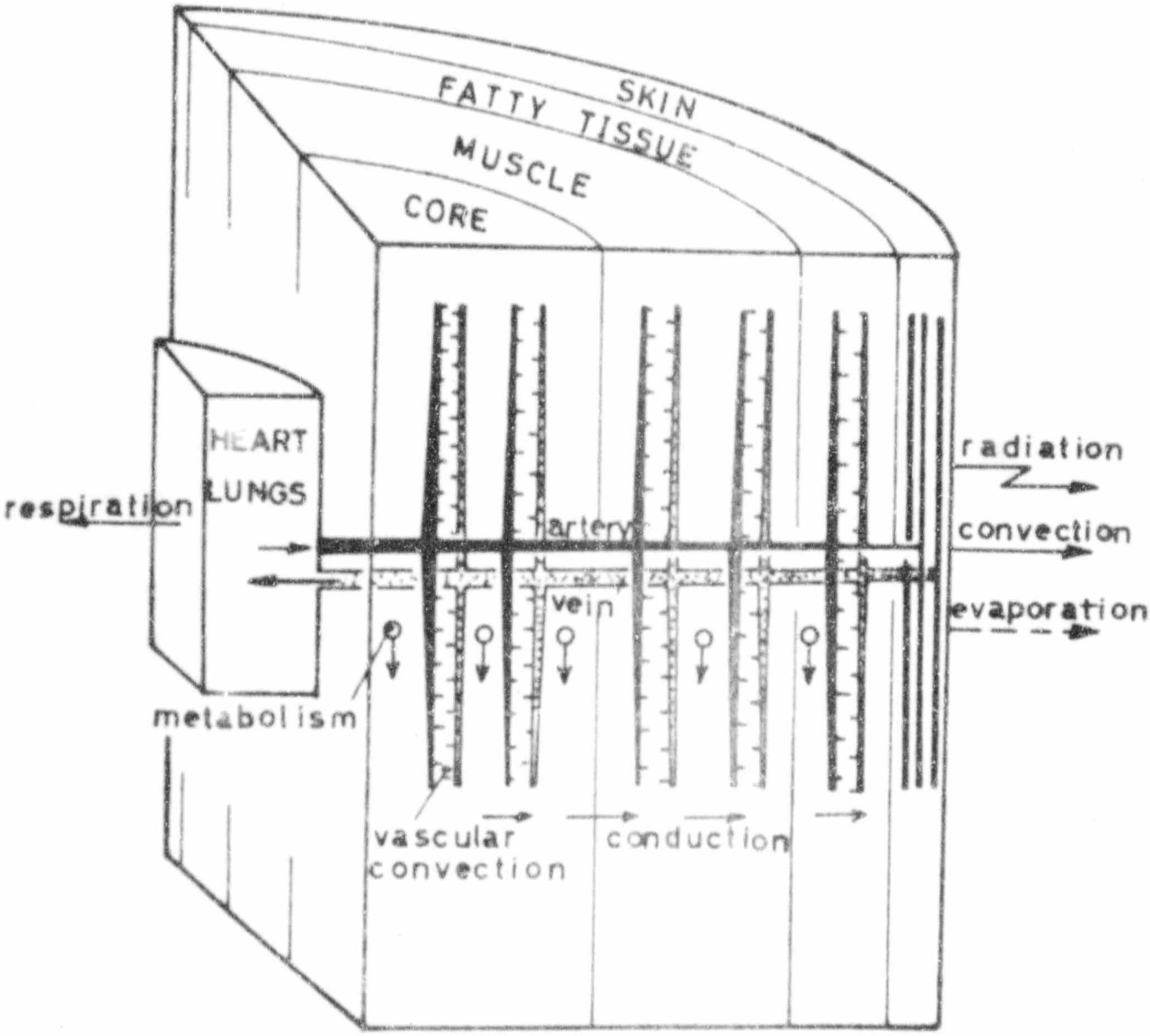

FIGURE 3.6

A schematic illustration of a cylindrical model of the body: the controlled system.

TABLE 3.1

The thermal properties of the model

Subject weight	=	60 kg
Density	=	1,035 kg/m^3 x 10^3
Therefore cylinder volume	=	0,057 97 m^3
Surface area of man	=	1,8 m^2
Therefore assumed radius	=	0,114 3 m
Therefore length of cylinder	=	1,4 m
Surface area of cylinder	=	1,015 m^2
(Muscle is regarded to occupy 43% of the total weight)		
Therefore muscle volume	=	0,024 9 m^3
Depth of tissue	=	2 mm
Therefore volume of skin	=	0,002 m^3
Assume a depth of fatty tissue	=	10 mm
Therefore volume of tissue	=	0,009 6 m^3
Assume a volume of circulatory system	=	0,002 m^3
Therefore the remaining volume is the volume of the core	=	0,019 7 m^3
Specific heat of tissue	=	347 8 J/kgm °C
Specific heat of blood	=	385 5 J/kgm °C

The surface area of the model is less than that of the body because it does not have limbs. A correction factor must therefore be used if heat exchange from the body is expressed as a function of surface area.

The mean metabolic heat input obtained from experimental observations on a resting and a working subject are illustrated in Figure 3.7. The basal metabolism is divided between the core, muscle and tissue in the following proportions:

Core	82 %	
Muscle	16 %	
Tissue and skin	2 %	(Stolwijk and Hardy,1966)

No information is available regarding the quantity of heat produced by the heart. The additional heat generated by physiological activity is attributed entirely to the muscle.

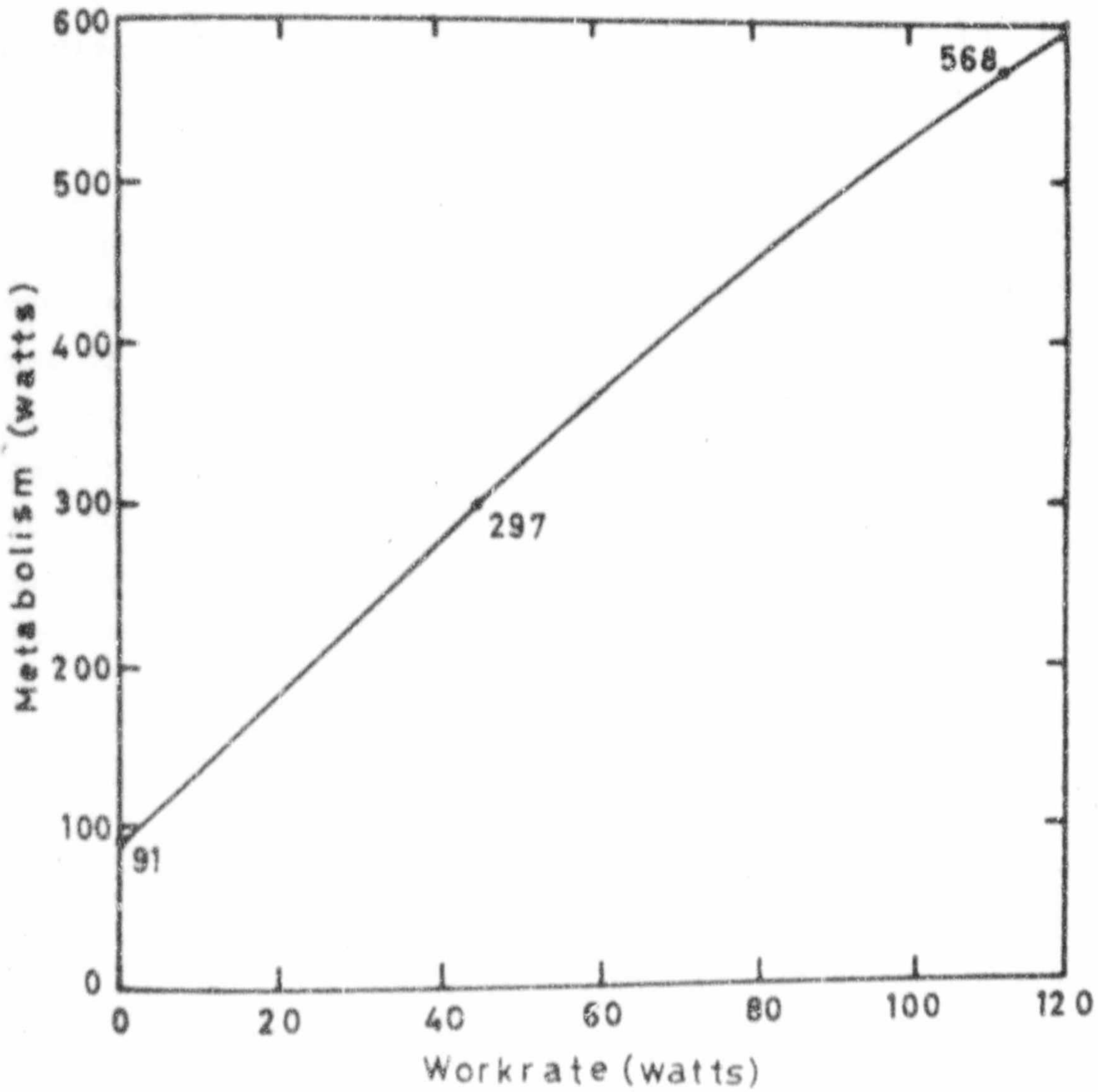

FIGURE 3.7

The relation between work rate and metabolism of a man pedalling in a climatic chamber.

3.4.2 Heat transfer by conduction

Although the major proportion of metabolic heat is transferred to the surface by vascular convection when man is in a warm environment, it is essential to examine direct heat conduction as this is significant in bodies in cold environments. The analysis applies also to the skin in which there is no circulation of the blood.

Radial heat flow in any homogeneous material is expressed by the partial differential equation (Chapman, 1960)

$$\frac{1}{r}\left[\frac{\partial}{\partial r}\left(r\,\frac{\partial T}{\partial r}\right)\right] = \frac{\sigma\rho}{k} \cdot \frac{\partial T}{\partial t} - \frac{h}{k} \qquad 3\text{-}13$$

The equation implies that tissue temperature is dependent upon both time and radius. The partial differential equation may be approximated by Taylor's expansion or by an iterative difference method (Atkins, 1960, 1962). The iterative method requires that the cylinder, or each zone of the cylinder, be divided into a number of small concentric step sections each having a width Δr and a radius r_n. The temperature in each section is given by the differential equation

$$C_n \frac{dT_n}{dt} = [K_{n+\frac{1}{2}}(T_{n+1} - T_n) - K_{n-\frac{1}{2}}(T_n - T_{n-1})] + H_n \qquad 3\text{-}14$$

For the sake of convenience, the conductivity is replaced by the term K_n which represents the conductance for the element section at n. Similarly, C_n is the total thermal capacitance for that section and H_n the total heat gain other than by conduction.

The temperatures at all values of n and time t may be determined provided the three parameters, the boundary conditions and the temperatures at time t=0 are known. The method of determining the parameters and the boundary values are given in Appendix A3. In order to solve the outer boundary quantities a knowledge of the rate of heat exchange between the body and environment is required.

The term H_n includes the net heat exchange in the section at radius r_n due to metabolic heat input and heat exchange by vascular convection. Therefore

$$H_n = H_{m_n} + H_{b_n} \qquad 3\text{-}15$$

where H_{m_n} is the rate of metabolic heat gain, and

H_{b_n} is the rate of vascular heat exchange.

The accuracy with which the thermal gradient can be represented depends upon the number of iterations, or finite steps, n. Where the thermal gradient is large, such as near the skin, the field should be represented by more steps of smaller dimensions.

3.4.3 Heat transfer by vascular convection

Assume a uniform distribution of blood in the core, muscle and tissue. Assume also that the heat exchange between tissue and blood is the same at all points on the same radius. This condition satisfies the assumption that heat flows in the radial direction only.

Consider a small segment, of unit volume, from either section of the cylinder. Let the volume of blood per unit of time entering the segment be m_n. If the temperature of the blood entering the segment is T_{v_n}, the rate of heat exchange with the tissue is given by

$$h_{b_n} = m_n\, c_b\, (T_{ar_n} - T_{v_n}) \qquad 3\text{-}16$$

If there is good thermal contact between the blood and the tissue it is safe to assume that the temperature of the blood leaving the tissue, T_{v_n}, is equal to the temperature of the of the tissue, T_n. For t is simple model it is also safe to assume that no counter-current heat exchange takes place between arteries and veins, apart from in the capillary beds. The arterial temperature is, therefore, uniform in all sections of the cylinder. Equation 3-16 may be rewritten as

$$h_{b_n} = m_n c_b (T_{ar} - T_n) \qquad 3\text{-}17$$

Equation 3-17 implies that the rate of heat exchange between blood and tissue, in any given segment of radius r, is proportional to

a) the rate of blood flow in that segment; and
b) the difference between the temperatures of the arterial blood and the tissue.

The total heat exchange for a section is given by

$$H_n = [h_{m_n} + m_n c_b (T_{ar} - T_n)] \times L\pi (r_{n+\frac{1}{2}}{}^2 - r_{n-\frac{1}{2}}{}^2) \qquad 3\text{-}18$$

The additional term on the right represents the volume of the section at n. Heat exchange is expressed as a total for each section.

Figure 3.8 illustrates a model of heat exchange in a segment n expressed by equation 3-18. The components of heat flow at each node are illustrated, the horizontal components representing conduction and the lower vertical components heat storage.

A simple heat transaction model such as that illustrated in Figure 3.8 is not sufficiently representative of the peripheral vascular heat exchange mechanism. Bazett (1949) and B. Nielson (1969) have shown that there is a large and variable thermal gradient within millimetres of the skin surface. (Refer to section 2.3.1 and Figure 2.1) It is difficult to explain the true nature of the presence of the peak in the temperature profile, if it does exist, and hence of a negative temperature gradient within a body which is losing heat.

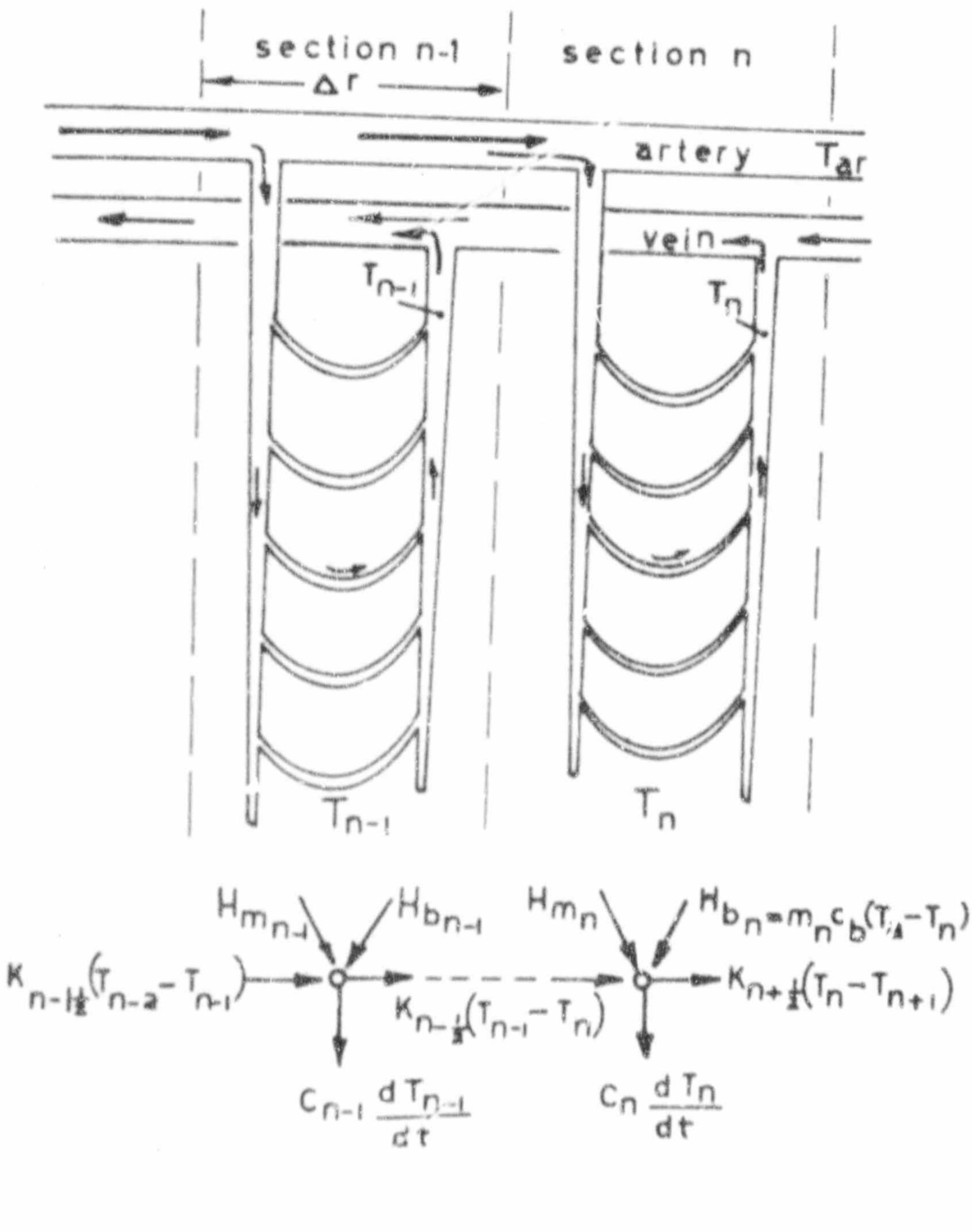

FIGURE 3.8

A schematic illustration of the components of heat transfer at a section n and the method of vascular convection.

The important fact is that there is a large temperature gradient in the peripheral region. Though little is known of the function and the distribution of the arterio-venous anastomoses and the capillaries, the heat exchange in this region should be considered rather carefully as this is where most of the heat is released from the circulatory system. The model of the controlled system should avoid the complexity of a peak in the temperature profile but retain a steep temperature gradient in, or near, the dermis.

A simple model of the periphery which takes account of the arteriolar plexus and the venous plexi, described above, is illustrated in Figure 3.9. This model should be compared with Figure 2.1. The radial sections of the model are chosen such that the first section in the skin (S1), adjacent to the fatty tissue, is in contact with a venous plexus. The second is in contact with the arteriolar plexus and the third contains the outer venous plexus. Section S4 contains the capillary loops beneath the epidermis. The epidermis is represented by section S5 through which heat is transferred by pure conduction. The outer section of subcutaneous fat and tissue, F, has capillary loops between arterial and venous vessels similar to those described for the muscle and core. It is assumed that there are arterio-venous shunts from section S2 to section S1 and from section S2 to section S3.

A portion of the arterial blood entering section S2 is shunted via the arterio-venous anastomoses to section S1 and to S3, the remainder flows through capillary loops in section S4 to the venules. The quantity of blood flowing through the 'shunts' will depend upon the extent of vasodilation or vasoconstriction (vasomotor- tone). The quantity of blood flowing through the capillaries will depend upon the activity of the pre-capillary sphimcter which open and close in a random manner. Because there are a large number of capillaries, the mean value of blood flowing through the capillaries is probably steady for a given control action. The mean value of the rate of blood flow through the capillaries changes with temperature. It is not

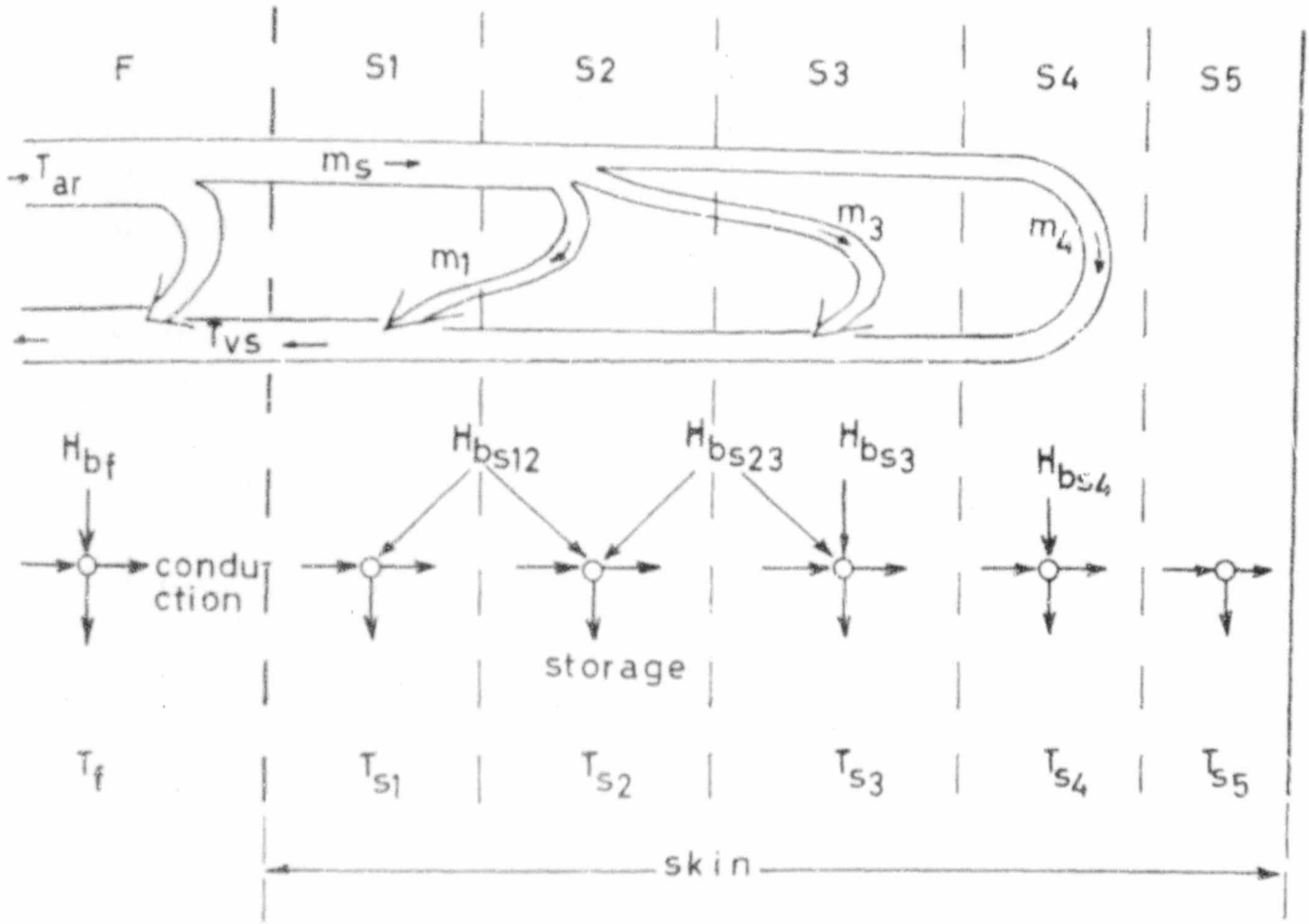

FIGURE 3.9

A schematic illustration to show how the peripheral blood is assumed to flow in the skin. The skin is divided into five thermal zones, the heat flow components of each zone are illustrated.

known whether the activity of the sphimcter is controlled by the same control action as that which controls the contractile walls of the arterio-venous anastomoses. For the purpose of this study, and unless there is a reason to change this hypothesis, it is assumed that the rate of blood flow through the capillaries and through the arterio-anastomoses are governed by the same control action.

Because neither the disturbance of the peripheral blood nor the boundaries of each section are clearly defined, it is not possible to evaluate the proportion of heat distribution in each section of the dermis. For this reason a simple mathematical model, which can represent the thermal gradient in the periphery and take into account changes in capillary action or vaso-motor tone, will be suitable for this study of the control actions.

The analysis of the model is given in Appendix 5. The analysis shows that there is a heat exchange between the circulatory system and the tissue in sections S1, S2, S3 and S4, of the dermis. The heat exchange is proportional to the rate of blood flow and the difference in temperature between the arterial blood and the tissue. The rate of blood flow in sections S1, S2, and S3, namely M1 and M3, depends upon the state of the arterior-venous anastomoses and the rate of blood flow in section S4 depends upon the activi of the pre-capillary sphimcter.

The temperature of the blood leaving the skin is T_{VS} (see Appendix 5)

The venous blood from the skin will mix with that from the fatty tissue. The temperature of the venous blood leaving section F is calculated in the same manner as T_{VS}, assuming perfect mixing of the components from sections F and S.

Therefore

$$T_v = \frac{M_f T_{vf} + M_s T_{vs}}{M_f + M_s} \qquad 3\text{-}19$$

The blood leaving the capillary beds of all the sections of the body returns to the central blood pool, which is the heart and lungs. The temperature of the central pool will depend upon the temperature of the incoming venous blood.

Let the total volume rate of blood flow from the muscle region be denoted by M_m and the temperature of the venous blood returning from the muscle region be T_{vm}. The rate of vascular heat exchange with the muscle is, therefore, given by

$$M_m c_b (T_{ar} - T_{vm}) \qquad 3\text{-}20$$

This is equal to the sum of the heat exchange components in each section in the muscle zone:

$$\Sigma \left(M_n c_b (T_{ar} - T_n)\right) L \pi \left(r_{n+\frac{1}{2}}^{2} - r_{n-\frac{1}{2}}^{2}\right) \qquad 3\text{-}21$$

The same will apply to the core and the fatty tissue zones. Applying the First Law of Thermodynamics to the central blood pool, the rate of change of heat storage in the central blood pool will be equal to the net heat exchange with all the sections of the body plus respiration heat loss. Therefore

$$C_{HL} \frac{dT_{ar}}{dt} = M_c c_b (T_{ar} - T_{v_c}) + M_m c_b (T_{ar} - T_{v_m}) + M_f c_b (T_{ar} - T_{vf}) + M_s c_b (T_{ar} - T_{v_s}) + H_h \qquad 3\text{-}22$$

where H_h is the rate of respiration heat loss.

As one of the control mechansims, a change in temperature will cause either vasodilation or vasoconstriction to take place. Vasodilation causes an increase in the rate of blood flow to a region as well as an increase in the volume of blood in that region. The period in which this change in volume takes place is short in comparison with the thermal changes; however, the change in volume does account for a change in heat content.

Let the volume of blood in the muscle zone be denoted by V_{BM} . A more precise expression for heat balance in this section is, therefore, given by

$$M_m c_b (T_{ar} - T_{v_m}) = \Sigma (M_n c_b (T_{ar} - T_n) \, L \, \pi \, (r_{n+\frac{1}{2}}^2 - r_{n-\frac{1}{2}}^2)) + c_b V_{BM} \frac{dT_m}{dt} \qquad 3\text{-}23$$

where T_m represents the mean muscle temperature.

At the onset of work additional blood is redirected from the core and periphery to the muscle. The core contains a large reserve supply of blood. Work causes an increase in heart rate and, therefore, an increase in cardiac output. It is assumed that the increase in cardiac output will cause a proportional increase in the rate of blood flow throughout the body. The need for an increase in muscle blood in order to remove the additional heat from the muscle during work might exceed the increase in blood flow caused by an increase in cardiac output (Atkins, 1972).

The rate of blood flow at any part of the body is dependent upon both the vasomotor tone in that region and the cardiac output. If M_n(rest) is the rate of blood flow in section n when a subject is at rest in a neutral environment, the rate of blood flow for any other condition may be expressed as

$$M_n = M_n(\text{rest}) \, B_c B_v \qquad 3\text{-}24$$

where B_c and B_v are coefficients denoting cardiac output and vasomotor tone. Both of these coefficients have a value of unity for a resting subject in a neutral environment.

The above expressions are sufficient to explain the thermal state of the body provided the magnitude of the parameters are known. The parameters are listed in Table 3.1. The coefficientr B_c and B_v will have to be verified experimentally with a model.

3.4.4 Heat exchange with the environment

The subject of heat exchange with the environment has been explained by Mitchell (1972) and Mitchell et al (1969).

The three main modes of heat exchange from the body are radiation, convection and evaporation of sweat (H_r, H_c, and H_e). A small amount of heat is also lost by respiration (H_h).

3.4.5 Respiratory heat loss

The quantity is determined by the respiration rate, and the temperature and the humidity of the inspired air. There are two components; convection or sensitbile heat loss and evaporative heat loss. These quantities are obtained from psychrometric charts and, therefore, obtained by simple calculation. The total respiratory heat loss constitutes only about 16 per cent of the metabolic heat input of a resting man. Some results, determined by Mitchell (1972), are illustrated in Figure 3.10.

3.4.6 Radiant heat exchange

The rate of radiant heat exchange between a body and its surrounding is proportional to the difference in the fourth powers of their absolute temperatures, their emissivity and their effective exposed area. Mitchell has shown how the experimental results verify the theoretical expression, the emissivity of both a white and a black skin being very close to unity. He has suggested a simple linear expression which applies over the range of ambient temperature encountered in the climatic chamber experiments:

$$H_r = A_r/A_b \left[6{,}02 \, (T_{rad} - T_s) \pm 8{,}3 \right] \quad (\text{watts/m}^3) \qquad 3\text{-}25$$

where A_r/A_b is the ratio of the effective radiation area to the total body area, and

T_{rad} is the temperature of radiation.

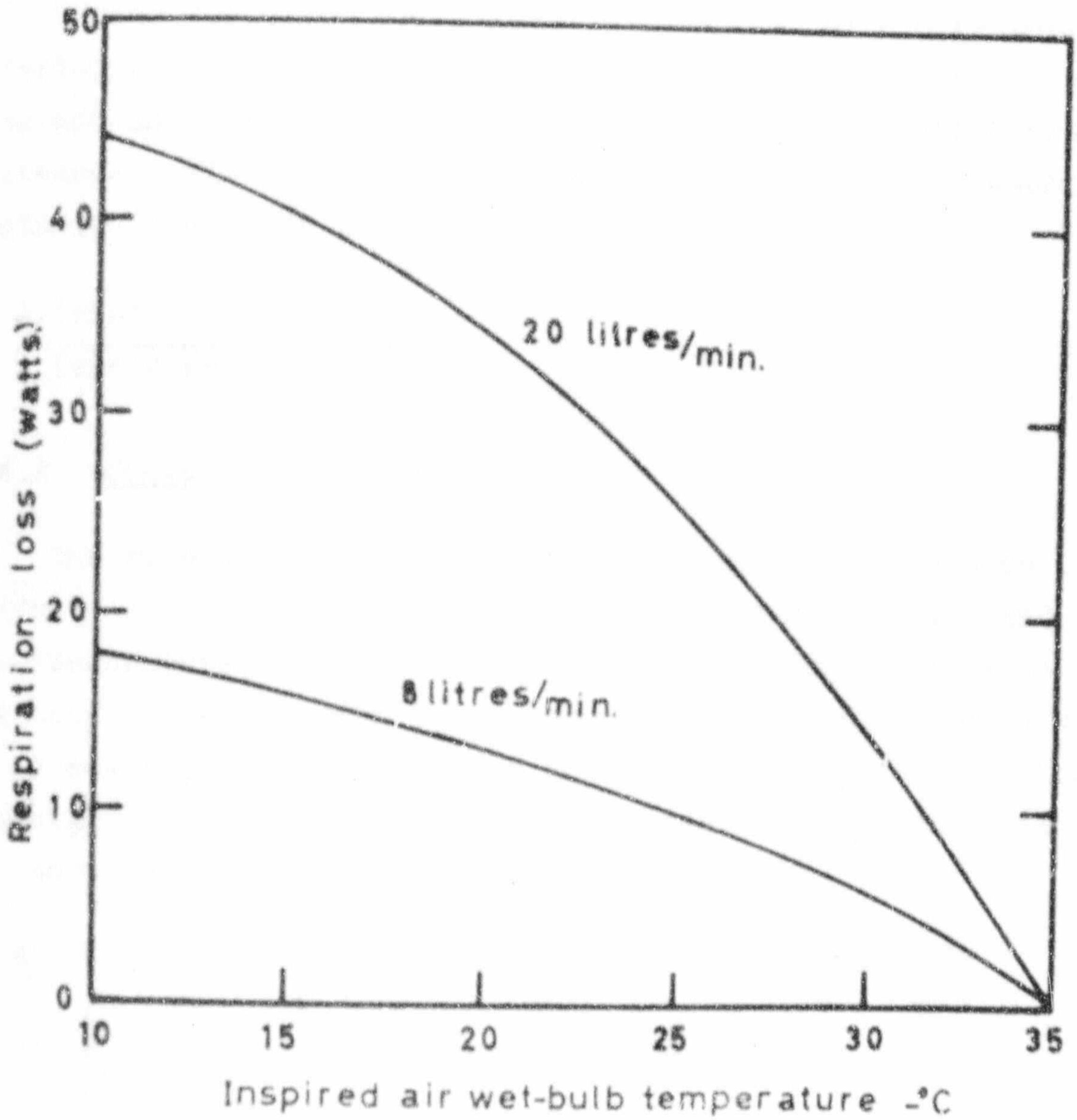

FIGURE 3.10

Respiration heat loss plotted as a function of wet-bulb temperature for two levels of respiration rate. (Mitchell, 1972)

The error in the value of H_r calculated by this expression is of the same order as the experimental error in measuring mean skin temperature with a fifteen-point scan. (Chapter 4)

During work, the fractional area available for radiation is affected because the mutual radiation between one part of the body and another is altered and the effective radiation area increases. Mitchell noted a constant 11 per cent increase in radiation area with exercise, that is,

$$\frac{A_r(\text{rest})}{A_r(\text{exercise})} = \frac{1}{1{,}11} \qquad 3\text{-}26$$

3.4.7 Convection heat exchange

The rate of heat exchange by convection depends upon the difference between the temperature of the body surface and the air temperature, the air velocity, and the shape and size of the body. The air velocities used during the experiments were, by necessity, in a range above that at which free convection was significant. Mitchell (1972) derived the following expression for heat exchange by convection:

$$H_c = (8{,}28 \pm 0{,}06)(P_a/1013)^{0{,}6}V^{0{,}6}(T_a - T_s) \quad \text{watts/m}^2 \qquad 3\text{-}27$$

where P_a is atmospheric pressure (mbar), and
V is the air velocity (m/s).

The coefficient applies only to the case of an upright body in horizontal air flow. This is the only equation which has been derived from direct experimental measurement. Other similar expressions have been suggested on the basis of data obtained by indirect calorimetry. Body movements during exercise increase the relative rate of air movement over the body surface. Mitchell noted that air velocities of 0,67 m/s and 3,11 m/s were increased by 0,33 m/s and 0,37 m/s, respectively, when the subject pedalled an ergometer at a rate of 60 r.p.m.

It is safe to assume, therefore that there will be a mean increase in air velocity of 0,35 m/s, when the subject pedals at 60 r.p.m.

The two components of heat loss, H_r and H_c, may be combined to form a single linear expression if the temperature of radiation is equal to air temperature, namely

$$H_{rc} = H_r + H_c$$

$$= \left(6,02 \; \frac{A_r}{A_b} + 8,28 \left(\frac{P_a}{1013}\right)^{0,6} V^{0,6}\right) (T_s - T_a) A_b \quad \text{watts}$$

$$= K_{rc}(T_s - T_a) \qquad 3\text{-}28$$

where

$$K_{rc} = \left(6,02 \; \frac{A_r}{A_b} + 8,28 \left(\frac{P_a}{1013}\right)^{0,6} V^{0,6}\right) A_b$$

3.4.8 Evaporative heat loss

A large proportion of heat is lost from the body as the latent heat of evaporation of sweat. Thd body controls the rate at which sweat is secreted to the surface. There is a maximum rate at which this sweat will evaporate. If all the sweat does not evaporate the remaining portion merely drips off the body.

The maximum rate at which sweat will evaporate depends upon

a) the difference between the water vapour pressure of the air and the saturated water vapour pressure at the skin temperature, and

b) the air velocity.

It is not entirely correct to assume the heat of evaporation of sweat to be equal to the latent heat of vaporization of water at skin temperature. A discrepancy of approximatly 7 per cent has been reported by Snellen et al,(1970), and others. No explanation has been found for this error. (Surprisingly, no one has challenged the accuracy of the determination of metabolic heat input from oxygen intake)

Taking this discrepancy into account, Mitchell found the heat of evaporation of sweat to be 2 600 J/g or 43,3 W min/g.

The maximum amount of heat lost by evaporation from semi-nude or nude men in transverse windflow is given by Mitchell (1972) as:

$$H_e(max) = (15\,100/P_a)\ (P_a/1\,013)^{0,6} V^{0,6} (P_a - P_s) A_b \text{ watts} \quad 3\text{-}29$$

where P_a is water vapour presssure of air, and
P_s is the saturated water vapour pressure at skin temp.

When the body is not saturated the sweat rate, and hence the rate of loss of heat by evaporation of sweat, is dependent upon the thermo-regulatory mechansim.

Body movement, caused by pedalling the ergometer, will affect evaporation in the same way as convection and increase the air velocity by 0,35 m/s.

3.5 Summary

Both the controller and the controlled system have been analysed. It is assumed that they have a non-linear response, however, if small excursions are considered the response of each excursion may be represented by a linear equation. The form of the equation representing the controller is given by 3-12. The form of the equation representing the controlled system will depend upon the number of segments 'n' chosen to represent this distributed system (see equation 3-14).

It is clear that a mathematical analysis of a distributed system which is represented by a large number of segments is difficult. An initial identification of a system should be kept as simple as possible. The information derived from a simple examination is then tested in a more complex situation with a simulation model.

Experimental evidence described in the previous chapter has shown that there is a large thermal gradient near the periphery. It is therefore possible that a simple model of the controlled system, represented by two segments, and proposed by MacDonald and Wyndham (1950), is adequate for an initial investigation. Before this assumption is made the dynamic temperature response of man must be examined.

The environment temperatures of interest to the mining industry are in the range from 28°C to 45°C. This study will include the range from 13°C to 28°C. The steady state temperature response of the body in this region shows that if a step disturbance in air temperature is confined to a change of 2,5°C (Mitchell , 1972), the rectal temperature will not vary by more than 0,2°C. According to the sweating characteristics given by Wyndham and Atkins (1968) both the controller and the controlled system should retain a linear response within this range of disturbance.

CHAPTER 4

AN EXAMINATION OF THE THERMAL RESPONSE OF MAN IN A CALORIMETRIC WIND TUNNEL

4.1 Introduction

In this chapter is described the experimental work performed on men in the calorimetric wind tunnel (c .matic chamber) with the object of studying their thermal behaviour in a variety of environments. Six series of experiments were conducted, the first two may be regarded as preliminary experiments. After an examination of the data from these experiments the author planned the Series 4,5 and 6 experiments for more accurate and detailed data. Because of the large quantity of data which was accumulated only a few examples and a summary of the experimental results are included in this chapter. Further experimental results appear in the Appendix. The results are examined in chapters 5,6 and 7.

Figure 4.1 illustrates a subject in position in the climatic chamber during a typical experiment. Figure 4.2 illustrates the electronic monitoring equipment which is outside the chamber. Table 4.1 lists the variables which were measured during an experiment.

The climatic chamber and the measuring instruments are described in Appendix 1. The description shows the vast amount of preliminary design that was necessary to develop equipment for this type of study. Part of this equipment was made by the author. Reference is made in the Appendix, to persons other than the author, who were responsible for part of the design of the equipment.

TABLE 4.1

The physiological variables which were measured.

Mean skin temperature	Oxygen consumption
Rectal temperature	Respiration rate
Oesophageal temperature	Work rate
Radiant heat loss from the body	Heart rate
Convective heat loss from the body	Change in weight of the subject.
Evaporative heat loss from the body	

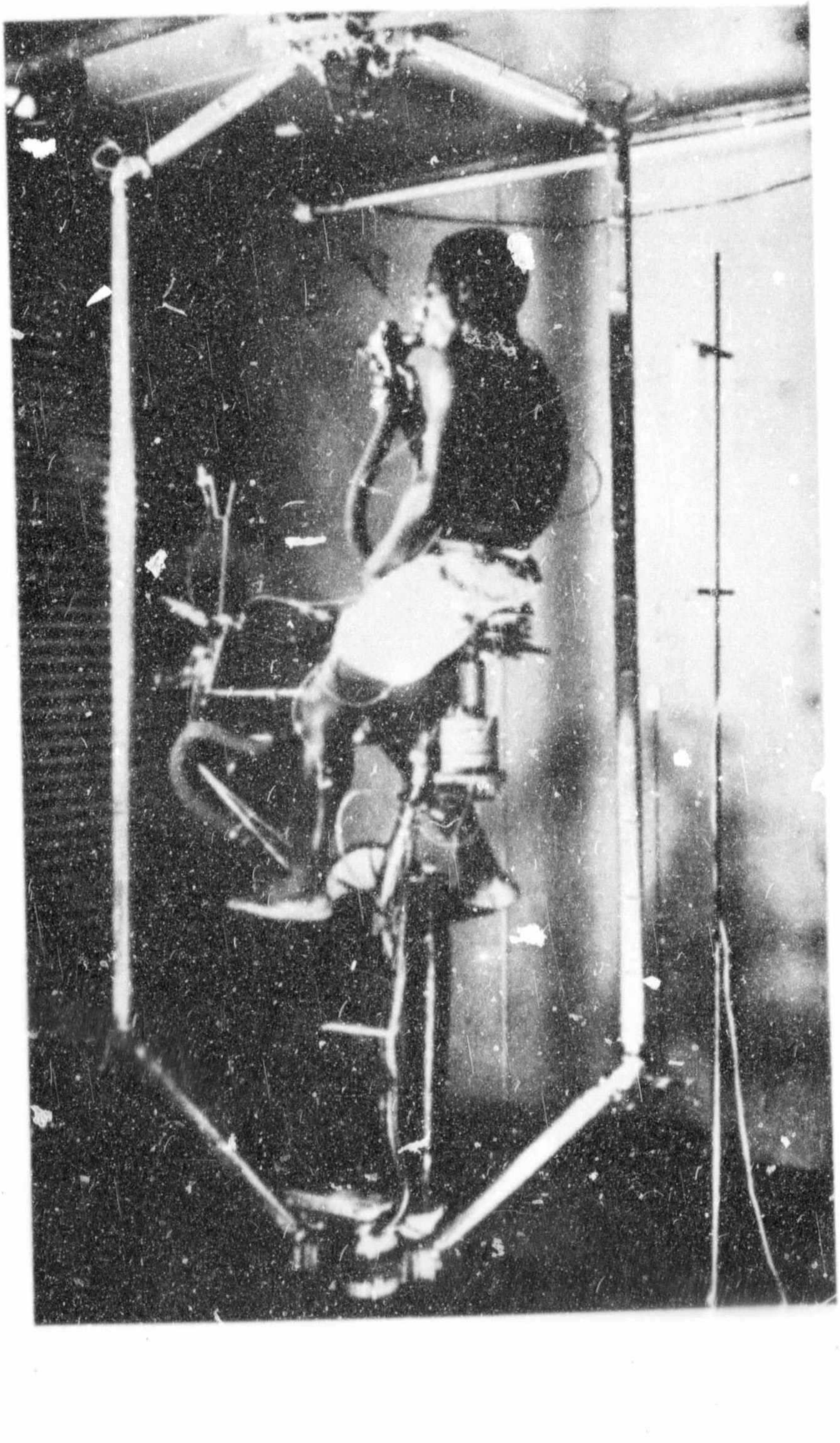

FIGURE 4.1

The climatic chamber with a subject in position on the bicycle ergometer.

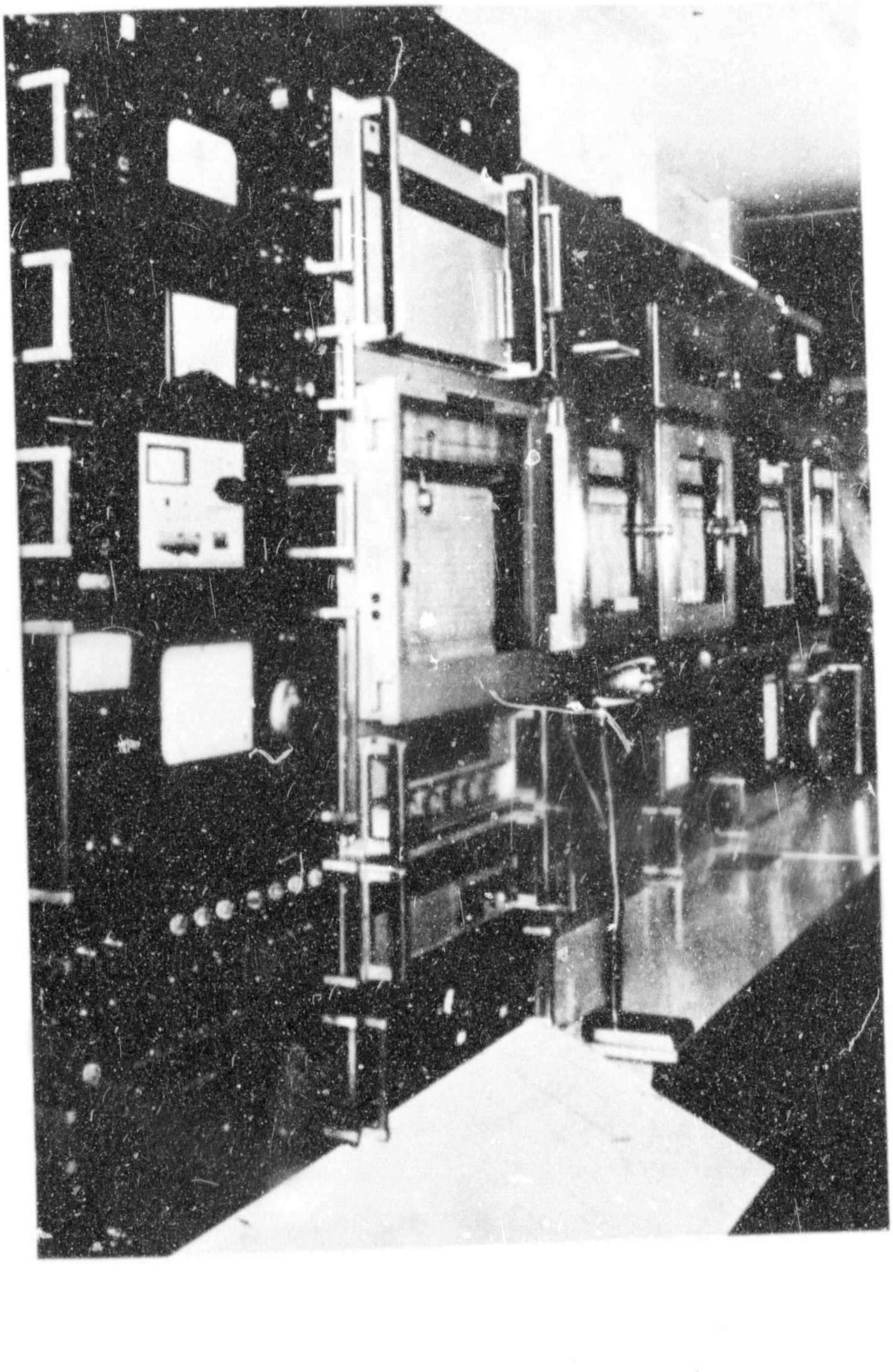

FIGURE 4.2

The instrument console for physiological measurements.

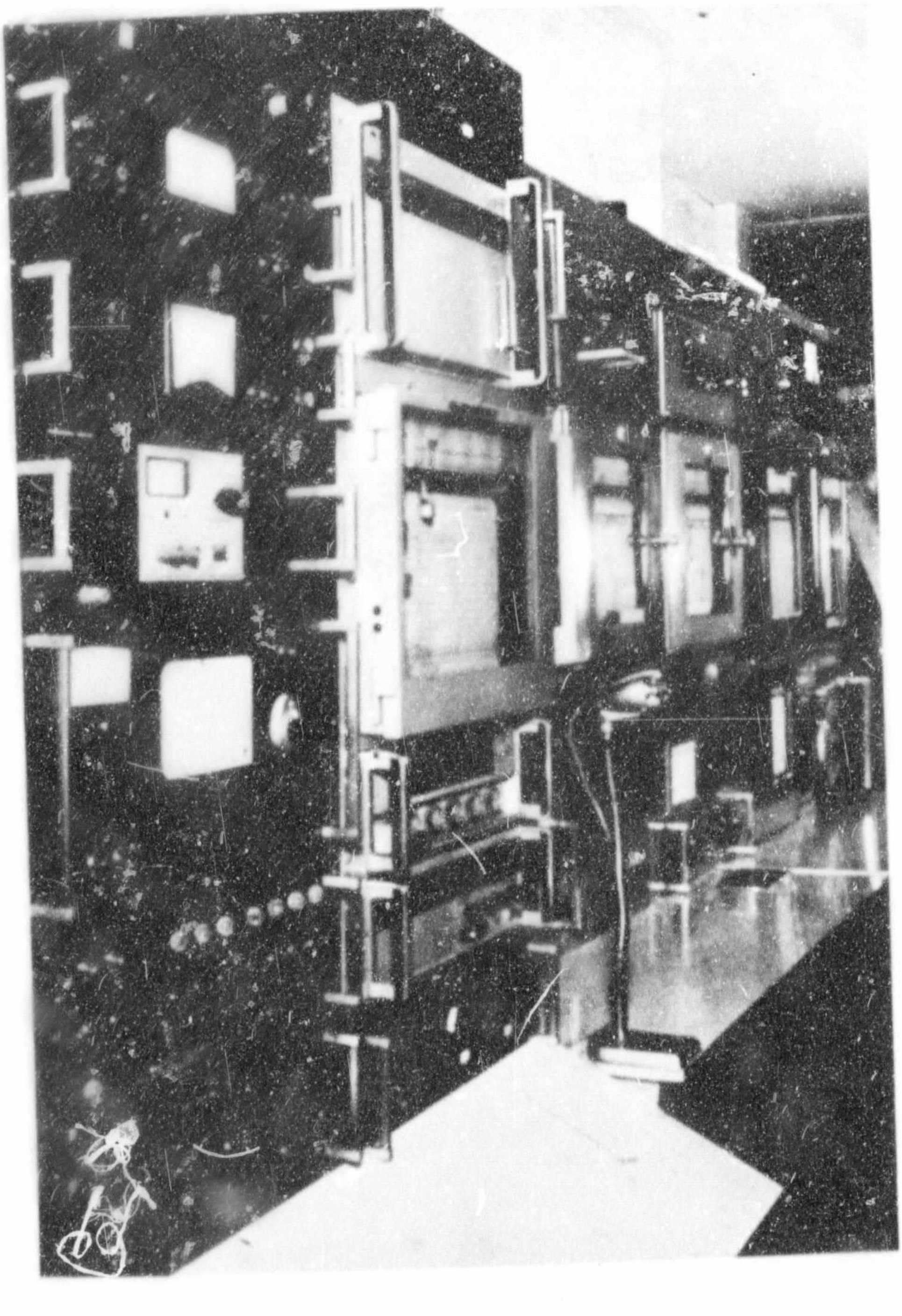

FIGURE 4.2

The instrument console for physiological measurements.

The author assisted with the Series 1 and 2 experiments and personally conducted the Series 4 and 5 experiments. He was responsible at all times for the instruments used for measuring and recording of data in all the experiments.

4.2 The experiments

Experiments performed in the climatic chamber must be carefully planned as a considerable amount of time is required in which to select, train and acclimatise a subject in preparation for an experiment. Each set of experiments is time-consuming and expensive.

Three series of experiments were conducted in the climatic chamber between 1966 and 1969. These were the first in which use was ever made of direct calorimetry. The experiments were designed for the systematic exploration of the effects of three environmental parameters, namely, air temperature, wind speed and humidity on the thermal responses on men at rest and when doing positive work.

The two objectives of the experiments were to

(a) derive a reliable expression for heat exchange between man and his environment;

(b) investigate the thermoregulatory characteristics of man so as to be able to predict physiological strain.

Since the mining industry is concerned with young healthy acclimatised men, only subjects in this category were used in the experiments. The influence of clothing was not investigated, the subjects were clothed only in athletic shorts. Before each experiment a number of healthy subjects with typical body dimensions were interviewed. Two of the most intelligent and co-operative were selected, acclimatised and then trained. When an experiment involved the performance of work, the subjects underwent a period of a few weeks of training on a bicycle ergometer similar to the type described above.

Series 1

The experiments were designed to investigate the influence of environmental temperature and of air velocity on the heat exchange between acclimatised hydrated men and their environment. A low humidity was used to ensure adequate evaporation of sweat. Two subjects were used for the experiments. Each subject was exposed to the 25 environments listed in Table 4.2. (see end of chapter, page 106)

The men rested in an air-conditioned preparation room with an air temperature of 28 °C for 60 minutes before entering the climatic chamber in which they sat for 120 minutes. The subjects were removed from the climatic chamber after 60 minutes, in experiments 4 and 5 because of their low rectal temperatures.

Series 2

These experiments were an extension of the first series and included the additional variable work rate. Two subjects were used in the experiments. The number of environments was reduced because of shortage of time. Because it was not safe for the subjects to work at the highest air temperature used in Series 1 this condition was excluded. The humidity was kept at a low level at all times. After an initial rest at an ambient temperature of 28 °C the subject entered the climatic chamber and rested for a further 40 minutes before working for 120 minutes at three levels of work. The experimental conditions are listed in Table 4.3. (see end of chapter, page 107)

Series 3

This was the most comprehensive study. The additional variable, humidity, was included. Two subjects were used in the experiments. The initial conditions in the preparation room remained the same, the subjects rested for 90 minutes in the climatic chamber, worked for 90 minutes, then rested for another period of 90 minutes in the chamber. The effect of cooling after exercise was examined. The experiment was conducted in 17 environments and at three levels of exercise. The conditions are listed in Table 4.4. page 108)

The first objective of these experiments was achieved successfully. The results have been published elsewhere (Mitchell et al., 1967a, 1967b and 1967c; Mitchell et al., 1968 and 1969). The information is all based on the steady state data. Mitchell (1972) has used the steady state data to examine the second objective, namely the study of the thermoregulatory characteristics of man. The data from these experiments and the data from a further three series of experiments, planned by the author and executed during the period 1972 to 1973 are used for the study described in this thesis.

Series 4

These experiments were planned after a study had been made of the results of the first three series of experiments and the conclusion reached that there was a need for more detailed experimental results.

There were five objectives:

1. To obtain a better record of the transient temperature characteristics during a step change to a warm environment. The mean skin temperature was measured more frequently and the rectal temperature was recorded on an expanded scale with a span of 2,5 °C.

2. To include the measurement of oesophageal temperature and to identify the difference between this record and the rectal temperature record, particularly in the early transient stages.

3. To measure the transient and steady-state evaporative heat loss and then to compare the correlation between these quantities with body temperature.

4. To examine the response of the body to small step changes in ambient temperature so that the control mechanism would remain within a relatively linear state. The amplitude of the step changes were small and the initial value of air temperature was varied.

5. To include a wider range of ambient temperatures and thereby to obtain a better comparison between steady state body temperatures and warm ambient temperature. These characteristics would indicate the range of ambient temperatures in which peripheral blood flow varies in a resting subject.

Two subjects were used for the experiments.

The experimental environments included a number of those used in the first series of experiments as well as three additional climatic chamber temperatures and four initial preparation room temperatures. The experimental conditions are listed in Table 4.5, page 109 .

Series 5

These experiments which were the opposite to those in Series 1 and 4, were designed to examine the thermoregulation during cooling of a resting subject after he had been exposed to a hot environment. Careful attention was paid to sweating as this component of heat exchange effects the settling time considerably. The subjects rested at various initial hot temperatures for 90 minutes and then entered the climatic chamber in which the air temperature was 28°C. The cooling experiments were conducted at two values of air velocity in the climatic chamber. The experimental conditions are listed in Table 4.6. Two subjects were used for the experiments.

Series 6

No trace of evaporation from the subject was recorded in the climatic chamber during the cooling experiments described in Series 5. Because of the initial delay in commencing recording it was not possible to determine how rapidly the evaporation ceased after the subject had moved from the hot to the cooler room. An experiment was therefore planned to record the evaporation continuously from a small area of the forearm with a hygrometer while this change in air temperature took place. The micro-hygrometer, described by Mitchell and Atkins (1966) was used by Mitchell to observe the effect of local heat on evaporation (Mitchell, 1972). The capsule was attached to the subject's arm and evaporation from the area covered was recorded.

A record of evaporation is illustrated with the experimental results in Figure 4.10. The evaporation decreased to less than 10 per cent of its initial value within ninety seconds.

4.3 Experimental procedure

The procedure for a typical experiment is as follows.

Once a subject had been selected, his mass, height, total surface area, effective radiation area and maximum oxygen intake were measured.

The radiant surface area of the body in the spread-eagle posture and that adapted for the bicycle ergometer are measured in the laboratory photodermoplanimeter which was designed specifically for the Human Sciences Laboratory by Halliday and Hugo (1963). The instrument, which is simple and accurate, consists essentially of a large integrating light sphere. The change in light intensity within the sphere due to the presence of a black body placed in the sphere is proportional to the radiant surface area of the body. The subject is painted with a matt black water-based paint for this purpose. The total surface area is taken as being 4,1 % larger than the radiant surface area of the body in the spread-eagle postion (Van Graan, 1969).

The maximum oxygen intake is measured by means of a standard laboratory exercise procedure. This quantity indicates the maximum rate at which a subject is capable of working.

An activity programme is planned for each series of experiments to avoid overlapping or confusion of personnel duties. The plan is displayed clearly on a board throughout the duration of an experiment.

The subjects, once they have been trained, are exposed to a standard laboratory acclimatisation procedure which lasts for at least ten days. During this period all the climatic chamber instruments are checked and calibrated. A trial "experimental run" is made to check the entire procedure before the experiments are commenced.

Each morning the subject is required to report at 7.00 a.m., having had a light meal. In order to stabilise his body temperature he has to rest for 90 minutes in an air-conditioned temperature-controlled preparation room. During the first 15 minutes the physiological monitoring probes for weighted skin temperature, oesophageal temperature, rectal temperature and heart rate are attached to his body. All equipment is then checked to ensure that it is functioning correctly. A set of electrical connectors in the preparation room enables the physiological data to be monitored in either the climatic chamber or the preparation room.

During the last 15 minutes of the stabilisation period the subject is given an opportunity to drink water and to urinate. He is then weighed, and his heart rate, metabolic rate and mean skin temperature are measured at least twice. The means of these measurements are taken to represent the initial conditions of the subject. Base lines for the radiation, convection and evaporation heat-exchange instruments in the climatic chamber are established during this time.

When all the preparations have been completed the subject covers his body with a light jacket which he wears while he walks the short distance of 10 m to the climatic chamber. A technician assists the subject to disconnect and then reconnect the necessary plugs and also helps him to mount the ergometer as quickly as possible. The procedure for transferring the subject from the preparation room to the chamber takes approximately 60 seconds. Recording of data commences the moment after a "start" button is pressed after the subject has entered the chamber.

The subject is required to sit on ergometer seat for the duration of the experiment and to pedal when necessary. No restriction is placed on his posture, though there is little choice in this. The mean skin temperature scans, the metabolism and weight loss measurements occupy his attention at frequent intervals so that there has never been a complaint of boredom. He is able to communicate with the operator and may select and listen to a radio programme if he so desires.

The subject is encouraged to drink water and to urinate if he desires during the weighing procedure when the quantity of liquid is noted. The quantity of water offered to him as calculated from his weight loss, is sufficient to replace loss of moisture due to sweating and urination. In this way the body weight is kept constant.

At the conclusion of the experiment after the subject has been dismissed, the baselines for radiation, convection and evaporation are re-established and these three instruments are then calibrated. The floating mean calibration for the previous three days is taken as the calibration factor for that particular day. Once the metabolic measurements have been completed by the laboratory staff, these and the calibration data are keyed into the data logger and the record then removed and despatched for processing.

4.4 Processing experimental data

The processing of the experimental data was a very laborious task before a data "logger" was installed. The present procedure is to despatch the paper tape record to the computer centre each afternoon. The results in the form of a print-out and graph are available by the following morning. The entire programme for this process, including initial editing, was written by A. Mitchell in PL-1 language. The plan of the programme requirements was drafted by D. Mitchell and the author. A flow diagram of the programme