Hensel (1973) states that the general neurophysiological properties of cutaneous thermoreceptors can be described by

a) they have a static discharge at constant temperature,

b) they show a dynamic response to a temperature change, and

c) they are not excited by mechanical stimuli.

It has been suggested that there are two types of thermo-sensitive neurons (Eisenman, 1972), namely primary thermo-detectors and thermo-sensitive inter-neurons. Most, if not all of the cold sensitive units found in the hypothalamus are inter-neurons.

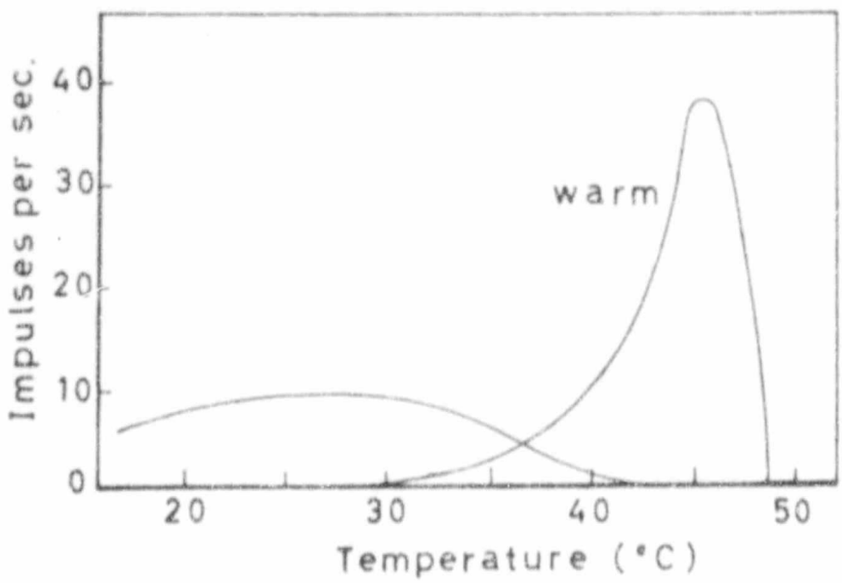

FIGURE 2.2

The temperature characteristics of cold and warm neuro-sensors taken from a single nerve fibre on the nose of a cat (Hensel, 1969).

The actual mechanism of the thermo-neuro transducer is not known. Electrical activity occurs at the terminal of the axon within the receptor. This generator initiates action potentials in the afferent axon by depolarizing it and causing the normal regenerative cycle, that initiates the conducted axon potential. The frequency of discharge is proportional to the amplitude of the generator potential (Iggo,1970). The afferent axon potential pulses are conducted to synapses in the hypothalamus. This region is regarded as constituting the central integrating neuronal control where electrochemical action occurs.

Some of the chemical constituents for control have been identified. Knowledge of their presence has assisted in the location of the position and density of these neuro-transmitters. Much has been learnt about transmitter function by introducing small quantities of the control chemicals into the cerebral ventricles and directly into the preoptic and anterior hypothalamic region. The chemical interference is thought to take place at the synapses in the hypothalamus.

On the basis of these and other tests a few neuro-transmitter models have been proposed in order to explain the interaction between the neuro-transmitter signals. Hammel (1965) suggested a model relating warm and cold receptors to heat loss and heat conservation reactions. Wyndham and Atkins (1968) suggested a model which accounted for transmitters from both the skin and the hypothalamus. Bligh and Cottle (1969) and Bligh and Maskney (1969) proposed a simple model to show how control chemicals acted upon the synapses. Bligh (1972, 1973) has studied these models in detail and has suggested a more comprehensive model which is similar to that illustrated in Figure 2.3. The inter-action between the neuro-transmitter signals is thought to exist in the so-called neuro-integrating centre in the hypothalamus.

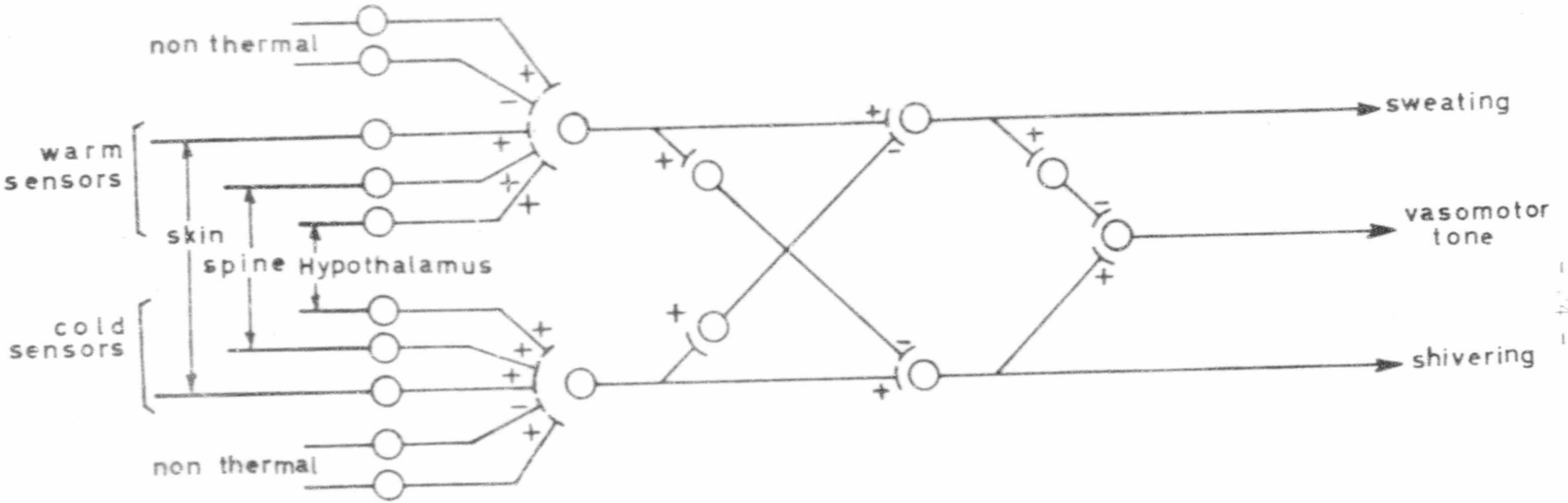

Figure 2.3

A neuro model illustrating the reaction between warm, cold and non thermal transmitted sensor paths. The synapses are represented by circles. The sign + indicates augment and the sign - , inhibit. (Bligh, 1972)

Bligh's model represents the relation between the cold and warm receptors and the control actions. The synapses are represented by circles. A positive sign indicates that the transmitted signal is augmented and a negative sign indicates that the transmitted signal is inhibited. The model indicates that a control mechanism such as sweating is the result of an interaction between a large number of warm and cold control sensors together with a possibility of non-thermal excitation.

If the warm sensors are given a positive sign and the cold sensors a negative sign, then the signal eminating from a synapses, for the purpose of control, will have a temperature characteristic similar to that shown in Figure 2.4. The curve represents the sum of the warm and cold sensor signals illustrated in Figure 2.2. A warm excitation will create a proportional increase in the degree of sweating and vasodilation whereas a cold excitation will result in the degree of proportional vaso-constriction and shivering.

There is evidence that the synapses and axons are themselves temperature-sensitive (Iggo, 1970).

Little is known about the efferent neuro-transmitters and the mechanism which links them with the control actions. The relationship between the firing rates or net signal from the hypothalamus and the control parameters, such as sweating is not known. Physiologists have, however, obtained fairly good correlations between body temperature and these control parameters (Wyndham, 1965; Wyndham and Atkins, 1968).

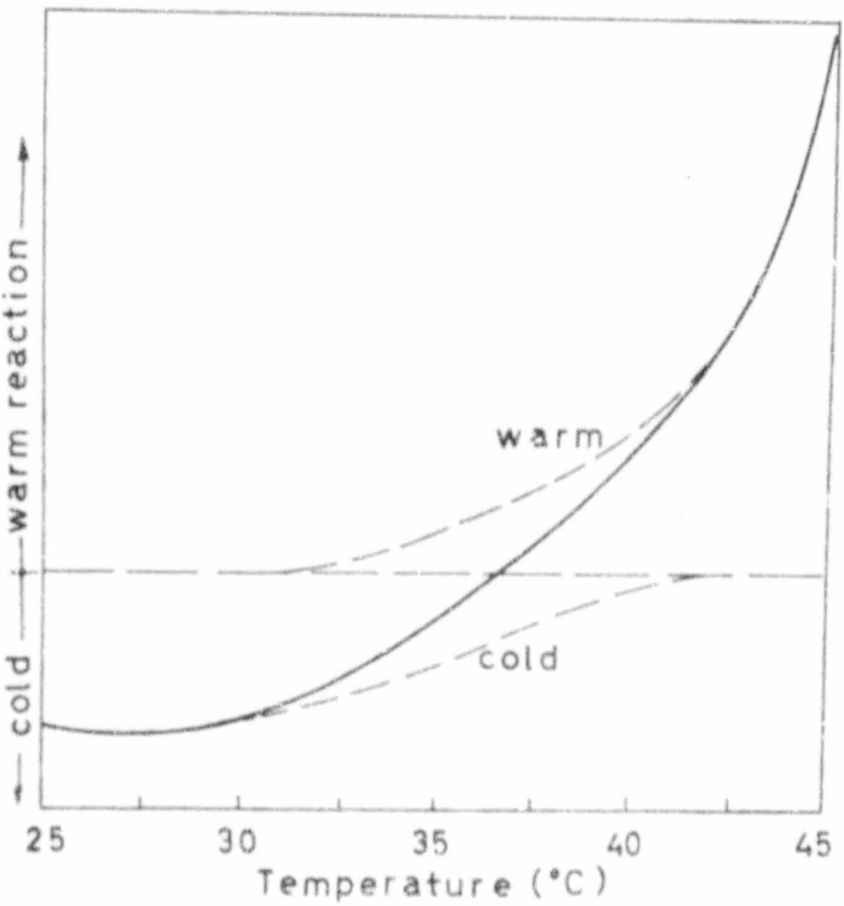

FIGURE 2.4

The cold and warm neurosensor characteristics are combined to form a single control curve. The cold sensor curve is inverted as these signals inhibit the warm signals. The control action is zero at 36,5 °C.

2.4.2 Control of sweating

The sweat control mechanism is the most powerful mechanism of combatting thermal stress. In a hot environment the rate of sweat secretion is adjusted such that the latent heat of evaporation of this sweat will maintain thermal equilibrium. There is a limit to the rate at which sweat can evaporate from the surface. Should the thermal demands exceed this limit, the skin surface becomes saturated with sweat and sweat will ultimately drip off the body so that thermal equilibrium can therefore, no longer be reached.

Physiologists have for some time endeavoured to correlate sweat rate with body temperature. The ability to sweat depends on the degree of acclimatisation (Wyndham et al.1954, 1967). Reproducible experimental results can, therefore, be obtained only if the degree of acclimatisation is held constant.

Robinson (1949) was the first to show a relationship between sweat rate as the controlled output, and rectal and mean skin temperatures. On the basis of the results of extensive experiments, MacDonald and Wyndham (1950) and Hardy (1961) supported this type of relationship. Benzinger (1963) on the other hand considered that sweating was entirely dependent on internal temperature.

The first quantitative relation between sweat rate, and rectal and skin temperature was given by Wyndham (1965). Sweating rate was found to be about four times more sensitive to rectal temperature than to skin temperature. Hardy and Stolwijk (1966) proposed the following simple linear expression for evaporative heat loss:

$$H_e = 5 + 80(T_e - 37{,}18) + 18(T_s - 33) \text{ Kcal/m}^2\text{/hr}$$

$$= 5{,}8 + 93(T_e - 37{,}18) + 21(T_s - 33) \text{ watts/m}^2 \qquad 1\text{-}1$$

Where T_e is the tympanic temperature (°C), and

T_s is the mean skin temperature (°C).

Wyndham, after further detailed experiments on a large number of subjects, obtained more precise results. A family of curves, illustrated in Figure 2.5 shows that the characteristics are non-linear (Wyndham and Atkins, 1968).

The greatest handicap in this work has been the lack of a sensitive and accurate instrument for measuring the total evaporation from the body. All the above data are based on a change in body weight. Bullard (1965) and Beaumont and Bullard (1965) developed an instrument for measuring accurately the amount of sweat which evaporates from a small area of the skin. Using this instrument, they confirmed that skin temperature plays a role in the control of sweating. However, the role is at least partially a local effect at the neuro-glandular junction, which does not involve skin thermosensors (Mac Intyre et al. 1968). Mitchell (1972) has shown that skin temperature effectively 'modulates' the sweating characteristics. He found that an increase in local skin temperature by directed radiation caused the sweat rate to increase from 4 to 7 g/m^2.min and suggested that the neuro-glandular junction of the sweat gland is temperature sensitive and may be regarded as a thermosensitive amplifier.

Nadel et al.(1971) made a detailed study of local sweating over the thigh, and were able to confirm a role for skin thermosensors. They have attempted to identify the relative importance between core and skin temperature by varying these temperatures independently of each other. The core temperature was increased by short periods of heavy exercise while the skin temperature could be adjusted with a radiation source. The relation between internal and mean skin temperature in the control of sweating rate is described by the summation model:

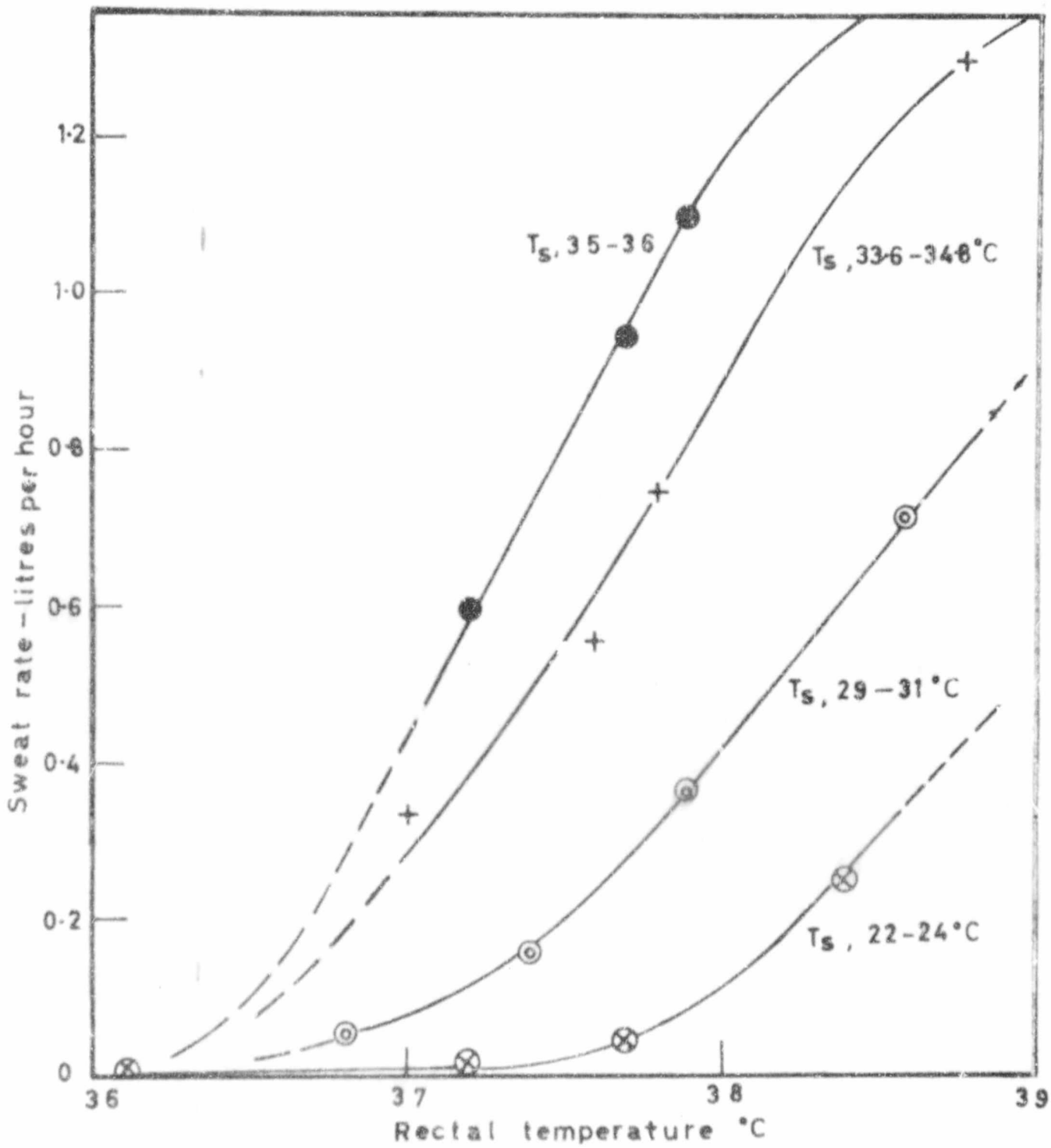

FIGURE 2.5

The sweat rate versus temperature characteristics given by Wyndham and Atkins, (1968).

(T_s = skin temperature)

$$H_e = 197(T_c - 36,7) + 23(T_s - 34,0) \text{ watts/m}^2 \qquad 1\text{-}2$$

By maintaining a portion of skin temperature constant at different levels during heating of this skin, Nadel was able to show that this skin temperature exerted a multiplicative, or modulative, effect on the output from the central controller. His complete model is given by the expression

$$H_e = 197(T_c - 36,7) + 23(T_s - 34,0)\, e^{(T_{ws} - 34)/10} \text{ watts/m}^2 \qquad 1\text{-}3$$

where

T_c is the core temperature,

T_s is the skin temperature, and

T_{ws} is the weighted skin temperature.

The multiplication term is highly non-linear and is significant only at a skin temperature above 35°C. Nadel also noted that during cooling of the skin the rate of change of skin temperature provided a significant signal to the central integrator and that sweating was rapidly inhibited. Banerjee and Bullard (1969) noted that the rate of sweating was depressed rapidly when a subjects legs were cooled in water. The extent of decrease was proportional to the rate of cooling and to the area which was cooled. The rate of sweating was restored to nearly its original level after a few minutes although the bath temperature was some 12°C lower than initially.

The large additional heat load associated with exercise is dissipated mainly by the evaporation of sweat. The additional stimulus required has not been identified. Experiments in the climatic chamber of the Human Sciences Laboratory have shown that there is only a small increase in rectal temperature after a period of work despite a large increase in the amount of sweating (Atkins, 1971; Mitchell, 1972). It has been suggested by Robinson (1963), Gisolfi

and Robinson (1970) and others that there are probably thermo-receptors in the muscles, though they have never been identified. Bradbury et al.(1964) found that sweat rate increased with the expenditure of energy, even at an elevated body temperature. They suggest that exercise stimulates sweating by some factor other than a rise in body temperature. Nielson, B. (1966, 1969), when studying both negative and positive work, found that the rate of sweating did not correlate with deep body temperature or oxygen intake but did with the amount of heat produced. She suggests the possibility of the release of chemical factors during work to stimulate sweating, (1968). Non-thermal excitation, such as mechanical excitation, may also possibly occur. Mitchell (1972) has shown that the correlation between sweat rate and change in mean body temperature for a resting subject is closer than that between sweat rate and rectal temperature. Because of the high muscle temperature it is not possible to determine the change in mean body temperature during exercise. The author has shown with a model that the mean body temperature increases substantially with exercise and might therefore provide the additional stimulus. Mitchell et al.(1972), and Atkins and Mitchell (1971) have suggested that work might cause an increase in the control sensitivity.

Snellen (1972) in a review suggested that if average body temperature is the proper input signal then the regulation mechanism operates as if there is heat regulation of the quantity of heat in the body rather than regulation of the temperature of the body.

2.4.3 Control of blood flow

In a mild, cool or warm environment the body is able to control the rate of heat flow to the surface and hence the temperature gradient between the skin and the core. (Refer to Thauer,1965, for a review of the subject)

This gradient is reduced in a warm environment and increased in a cold environment so that a near constant core temperature is maintained. Physiologists have found it convenient to express the heat transfer between core and skin in terms of a linear apparent physiological conductance, K_b, such that at steady state (MacDonald and Wyndham, 1950),

$$\text{Metabolism}, H_m - \text{Respiration}, H_h = K_b(T_{core} - T_{skin}) \qquad 1\text{-}4$$

A change in the temperature gradient between core and skin represented by a corresponding change in K_b is determined mainly by the state of the peripheral blood flow. Mitchell (1972) has shown that the physiological conductance for a resting man varies only within the ambient temperature range of 28 °C to 35 °C. At temperatures above this range the steady-state temperature gradient is constant. Mitchell states that the constancy of the conductance at low air temperatures is probably an artefact due to a change in the pattern of heat flow. The amount of heat transferred by vascular convection is reduced and is ultimately less than that transferred by pure conduction. There is evidence that peripheral blood flow decreases at ambient temperatures below 28 °C (Thauer, 1965). Wyndham et al. (1968) have shown that the physiological conductance decreases a further 30 per cent at air temperatures less than 25 °C, and that it appears to reach a minimum at 20 °C for a lightweight man and 15 °C for a heavy man.

The value of a single physiological conductance for representing the thermal gradient between core and skin during work is doubtful because of the intermediate high muscle temperature.

Physiologists have endeavoured to correlate physiological conductance with body temperature. The most detailed study was made by Mitchell (1972) who compared

physiological conductance with skin temperature, mean body temperature, oesophageal temperature and rectal temperature for a variety of ambient temperatures. Only resting conditions were considered. The best correlation, $r = 0,8$ was obtained when skin temperature was compared with conductance. The oesophageal temperature provided a slightly better correlation, 0,66, than mean body or rectal temperature.

Wyndham (1968) has plotted physiological conductance as a function of both rectal and skin temperature. Wyndham et al. (1968) reported that when two subjects were exposed to cold the physiological conductance fell sharply to minimum values as the average skin temperature fell to 27 °C. They state "the results suggest that in cold conditions vasoconstriction of peripheral blood vessels is directly related to the level of skin temperature." Keatings (1972) claimed that direct (local) effects of cold on vessels are as important as reflexes (from the core) in producing both increases and decreases in peripheral blood flow that can be induced by cold.

The change in thermal gradient between core and skin is due almost entirely to a change in the peripheral blood flow Thauer(1965).Hewlett and van Zwaluwenburg (1910) were the first to measure this change in blood flow and found that the extent of skin blood flow increased by a factor of five when the body temperature was elevated from 37 °C to 40 °C. Several workers have subsequently found an increase in peripheral blood flow following an increase in either body or skin temperature (van Rensburg, 1971). Little quantitative information is available because of the great difficulty in measuring peripheral blood flow. The usual technique is to measure the change in mean diameter of a limb with a plethysmograph. Calibration of such an

instrument is very difficult and it is impossible to ascertain what proportion of the change in diameter is caused by peripheral blood flow. Spealman (1945) compared the blood flow in cold, normal and warm environments while keeping the plethysmograph at a constant temperature of 15 °C. It was assumed that the local skin temperature was the same as the plethysmograph temperature. Blood flow values of 1,9; 5,9; 20,6 and 0,3; 0,9; 5,5 ml/100cc/min were measured at 35 °C and 15 °C. Van Rensburg (1971) summarised the findings by saying "The skin blood flow is the result of an interaction of central, local and reflex effects of heat. These effects may either oppose or reinforce each other."

It is not surprising to find a correlation between skin temperature and physiological conductance if core and skin temperature do not follow parallel paths. A change in physiological conductance will cause a change in the temperature gradient between core and skin. If the core temperature is controlled then it is the skin temperature which will change as a result of the change in physiological conductance. Because there is a correlation between physiological conductance and skin temperature, it does not imply that skin temperature initiates the control of peripheral blood flow.

Brengelman et al. (1973) reported recently that they found vasomotor control independent of skin temperature and the rate of change of skin temperature in a resting man; control appeared to be dominantly a graded response to core temperature. In a carefully planned series of experiments they were able to make the skin temperature follow a double ramp and a truncated ramp pattern while they measured the forearm blood flow. The skin temperature varied from 32 °C to 40 °C. Only after the skin temperature exceeded 38 °C or after an increase in rectal temperature did the peripheral blood flow increase. Their results indicate that a change in skin temperature has only

a small influence on forearm peripheral blood flow; however, the effect of a rate of change of skin temperature on peripheral blood flow is less convincing. The rate of change of skin temperature was relatively slow.

The author (Atkins, 1962) reported that if peripheral blood flow control was initiated by skin temperature, his analogue model became unstable. He stated (Atkins and Wyndham, 1968) that blood flow control is initiated mainly by the core temperature.

Unfortunately, there is no record of an experiment designed specifically to test the effect of rate of change of skin temperature with the peripheral blood flow. Rowell et al. (Dec. 1971) have found that a sudden increase in skin temperature results in an immediate drop in splanchnic blood flow and a rapid increase in peripheral blood flow. They concluded that the rapid increase in peripheral blood flow must result from the decrease in splanchnic blood flow.

Because of shortcomings in the measuring techniques it is impossible to ascertain whether vasodilation/constriction takes place only in the superficial venous arteriolar plexus or also in the veins and arteries of the subcutaneous fat. It is impossible to distinguish between the heat exchange from arteriolar plexi and from capillary loops.

Exercise introduces additional problems. Brengelmann et al. (1973) suggested that the pattern of control of blood flow in exercising man is radically different from that of resting man. Van Rensburg (1971) measured peripheral blood flow in working subjects exposed to a neutral environment in which air temperature was 21 °C. He obtained a linear relation between peripheral blood flow and oxygen consumption with a correlation coefficient of

0,9. The blood flow varied from 4 (ml/100cc/min), for a resting subject, to 24 for men undergoing heavy exercise. This is of the same order of change as that observed by Spealman (mentioned above) for a change from a neutral to a warm environment without exercise. Unfortunately, van Rensburg did not repeat his experiments in a warm environment when maximum vasodilation may already have taken place.

The major problem is whether the peripheral blood flow does in fact reach a maximum when a resting subject is exposed to an air temperature of only 35 °C, as suggested by the upper limit of physiological conductance (Mitchell, 1972). If a man starts working after he is already in such an environment, does his peripheral blood flow increase further? There is no quantitative information with which to answer these questions.

Mitchell (1972) has shown two different curves, when physiological conductance is plotted against air temperature, for the two situations o work and rest. The conductance is appreciably higher when the subject works. He shows that work rate has little influence on physiological conductance when the humidity is low and when sweating is adequate. Skin temperatures are reduced and the larger temperature gradient between core and skin is sufficient to permit loss of heat. When humidity is high and the evaporative heat loss is inadequate the skin temperature does not decrease, and an additional strain is imposed on the peripheral blood flow. The fact that the physiological conductance is higher during work in an environment of low humidity does not necessarily mean that the peripheral blood flow increases during work. As mentioned above, the value of the physiological conductance can be very misleading if the subject is working.

Rowell et al. (Jan. 1971) have shown that the peripheral blood flow can increase during exercise in heat if the skin

temperature is increased suddenly. This indicates that saturation could not have taken place. The author had difficulty in reproducing the experimental skin temperatures of a working subject with a simulator (Atkins and Mitchell, 1972). He concluded that either there was a further increase in peripheral with work or that the peripheral blood flow was shunted further out into the skin. The results presented in Chapter 7 will help to explain this problem.

Van Rensburg (1971) and Rowell et al. (Jan. 1971) and others found that there is an immediate decrease in peripheral blood flow at the onset of work. Van Rensburg showed that the blood flow dropped to less than half its original value, then returned to its initial value within six to ten minutes, before increasing. Unfortunately, Rowell introduced other experimental changes before the flow increased. He showed, however, that if the skin temperature was high, the initial decrease in peripheral blood flow was negligible. The peripheral blood volume was only a small proportion of the total volume but, even so, this quantity was diverted temporarily.

During exercise additional oxygen is required by the muscles. This is achieved by an increase in the blood flow pumped through the lungs by the right heart and by an equal increase in the blood flow, pumped by the left heart, to the muscle.

Wyndham (1959) and Rowell (1969) have provided the very useful relationships between workrate and oxygen intake and between oxygen intake and cardiac output. It is fairly safe to assume that the change in blood flow in muscle and in the periphery, after the initial decrease at the onset of work, is of the same order as the change in cardiac output during moderate exercise. The cardiac output of a man, who starts to work at a rate of [illegible] watts,

will increase from 6 to 12 L/min.

Rowell et al. (1969) have shown that the cardiac output of a working man exposed to a high temperature, decreased by 15 per cent at high work loads and by 7 per cent at low work loads while the oxygen uptake remained unaltered.

There is evidence that at the onset of heavy exercise large quantities of blood are drawn from the periphery and core to supply sufficient energy to the muscles (van Rensburg, 1971 and Rowell, 1969; Wade et al.,1956). It has also been suggested that there is a direct exchange of blood between the mus. e and adjacent periphery (Cooper, 1959).

2.4.4 Control of heat production

The increase of heat production in cold exposure was first accounted for by Rubner (1902). He attributed this reaction partly to 'physical', that is shivering, and partly to chemical reactions. Some animals with 'brown fat' have since been shown to have a chemical means of increasing their metabolism (Bruck and Wunnenberg, 1971). Man depends upon shivering, that is involuntary muscular activity.

Shivering appears to occur only when the body is exposed to a relatively cold environment. At first, shivering is spasmodic and insufficient to avoid a heat debt (Spealman, 1949) but as the extent of shivering increases, the heat debt can be overcome provided that the cold is not too severe. The increase in metabolic heat is comparable with light exercise. Rates of heat generation as high as 400 watts have been measured. Hardy and Soderstrom (1938) provided a very useful curve showing that metabolic heat increases almost in proportion to the decrease in air temperature below 28°C. Wyndham et al.(1968) compared the increase in metabolism of a fat man with that of an average man exposed to cold. They reported that a sharp increase in metabolism occurred when

the average skin temperature fell below 30°C for the average man. It was suggested that the fat man became habituated to a lower skin temperature.

There is very little correlation between metabolsim and body temperature as steady state is rarely achieved during experimental periods of typically one to two hours. Mitchell (1972) found no correlation between rectal temperature and increase in metabolic h[illegible]. The correlation between change in mean body temperature and change in metabolic rate was about the same as the correlation with changes in skin temperature, namely r = 0,8.

2.5 Mathematical and physical models of thermoregulation

The first thermo-models of the body were mathematical descriptions. Pennes (1948) proposed an expression for radial heat flow in the forearm assuming a uniform distribution of metabolic and vascular heat exchange. Earlier Machle and Hatch (1947) presented an equation of heat balance

$$M + D - V = R + C + E \qquad 1\text{-}5$$

where M is the metabolic heat input,
D is the rate of change of body heat content,
R, C and E are radiative, convective and evaporative rates of heat exchange, respectively, and
V is the rate of heat exchange by respiration.

The first true thermoregulatory model of the human body, an electrical network suggested by MacDonald and Wyndham (1950) is illustrated in Figure 2.6. The analogy between rate of heat flow with electrical current and temperature with potential difference are employed. Thermal capacitance and resistance are analogous with electrical capacitance and resistance. Thermal masses are, therefore, represented by capacitors in the various body regions.

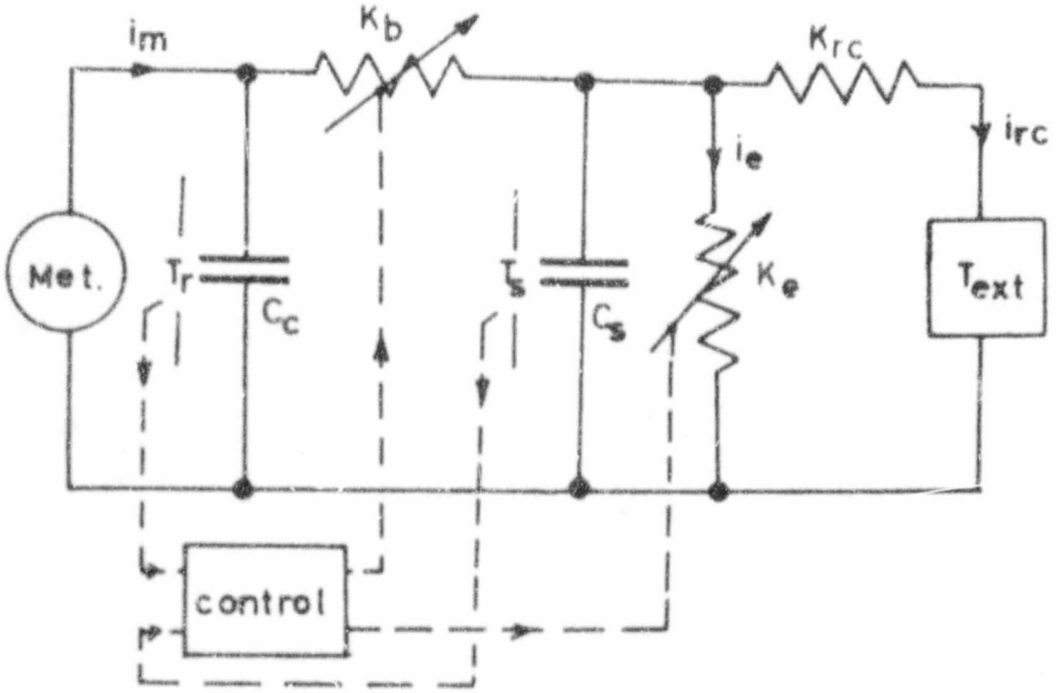

FIGURE 2.6

The electrical network model suggested by MacDonald and Wyndham (1950)

where C_c - core thermal capacitance

C_s - skin thermal capacitance

K_b - physiological conductance

K_{rc} - conductance for determining radiation and convection heat loss

K_e - conductance fo. determining evaporative heat loss

i_e - evaporative heat loss

i_m - metabolic heat input

i_{rc} - radiation and convection heat loss

T_{ext} - environmental temperature

T_r - rectal temperature

T_s - skin temperature

Heat flowing between regions encounters resistance (or conductance). Metabolic heat is represented by sources of current. Heat exchange between the body and the environment is represented by a resistance. The control actions for sweating, blood flow and metabolism are represented by the variable parameters.

Such a model is valuable in assisting with the solution of a problem as it clearly demonstrates the inter-relationship between the essential parameters and aids with the analysis of a system. This model is not intended to represent the precise nature of heat flow throughout the body but merely control actions and average thermal response to a thermal stress.

This simple electrical network model was the forerunner of many other models. Research under the guidance of Professor Taylor, University of California (1953 - 1957) took the first lead. Taylor's researchers modified the model by adding a further capacitance and obtained a few transient solutions of the model. The use of an analogue computer for simulating the thermoregulatory process was suggested by the author (Wyndham and Atkins, 1960). The author modelled the human body with a cylinder consisting of three homogeneous concentric sections which represented the core, the muscle and the skin. The conductivity of this model was treated as a variable in an attempt to replace the combination of pure heat conduction through tissue and variable vascular convection. A set of finite difference equations, representing radial heat flow in the body, was simulated with an analogue computer. The three control actions, metabolism, conductance and sweating based on experimental results, were controlled by function generators the characteristics of which were dependent upon both skin and core temperature.

Crosbie, Hardy and Fessenden (1961, 1963) followed with a similar analogue computer model in which was used

an infinite slab configuration instead of a cylinder. Their control actions were governed by a computed value of mean body temperature. The model results compared favourably with a few experimental results.

At this time Wissler (1959, 1961) examined the steady-state heat transfer mechanism of the entire human body. He realised the importance of separating the two heat transfer components, namely, conductance and vascular convection. Wissler described a passive steady-state model and presented a detailed analysis of heat distribution in the body. His model consisted of six elements which represented the torso, head, two arms and two legs.

The author (Atkins 1962, 1963) used an analogue computer to simulate his thermoregulatory model. The model which is illustrated in Figure 2.7, contained four concentric sections representing the core, the muscle, deep tissue and the skin. A single cylinder was chosen in preference to a number of elements as all heat exchange measurements and even skin temperature are expressed as a mean for the whole body. It would be very difficult at this early stage to isolate measurements for each individual limb. Heat transfer from the core to the surface by conductance and vascular convection were separated and a central blood pool distributed blood to the three inner sections. The influence of sweat control, blood flow control and metabolic control on body temperature were demonstrated.

Similar multi-layered one-dimensional models have been constructed by Brown (1963), Smith (1964) and Stolwijk and Hardy (1966). The model proposed by Stolwijk and Hardy consisted of three cylinders representing the head, the torso and the extremities. Each cylinder was sub-divided into three concentric layers. There was conduction of heat between adjacent layers and convective exchange of

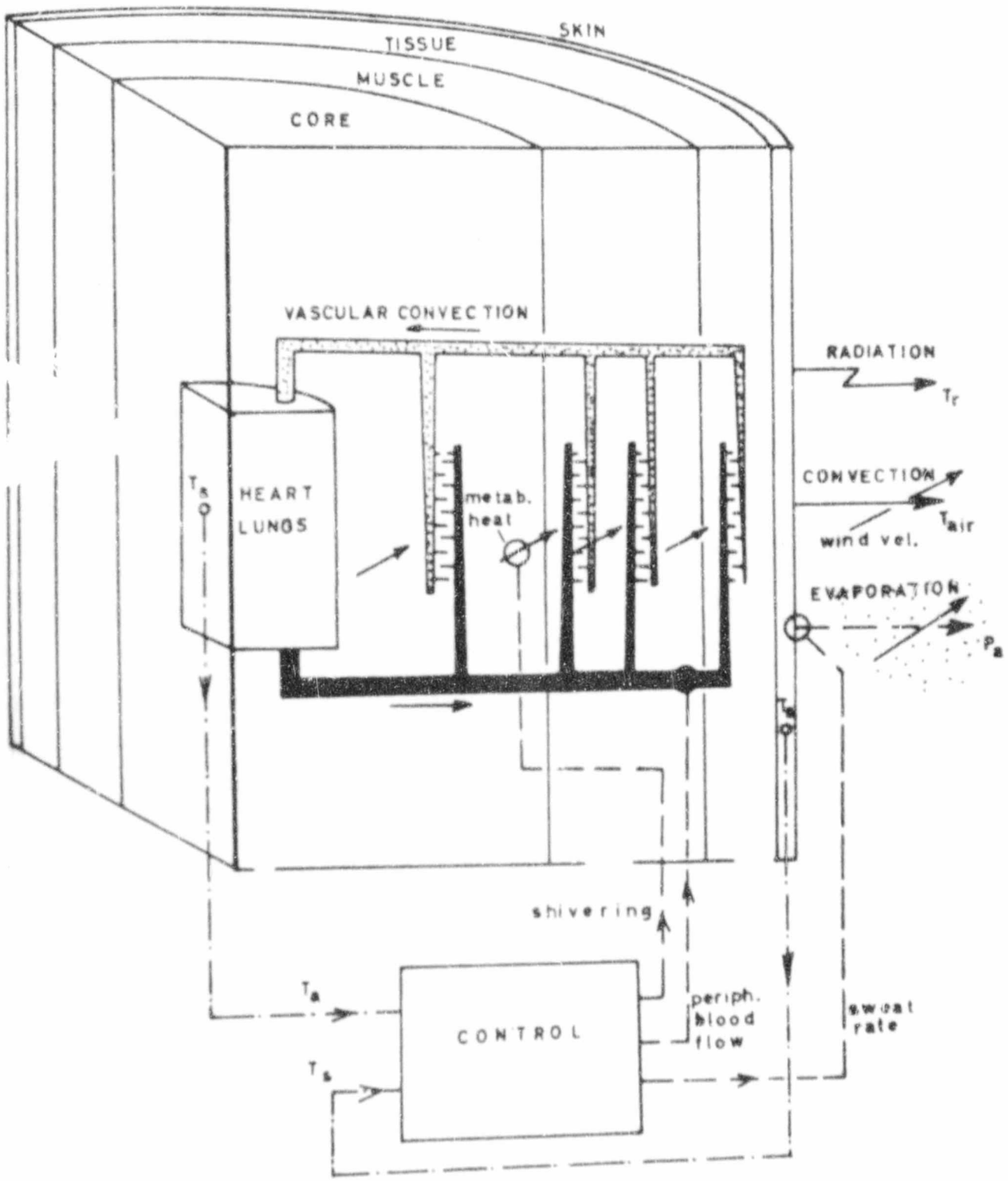

FIGURE 2.7

The physical model simulated with an analogue computer. (Atkins 1969)

heat between each layer and a central blood pool. Control was initiated from the core of the head, namely by hypothalamic temperature, and skin temperature. The model reproduced a few experimental results. Stolwijk and Hardy stated that the model could be useful to a physiologist in planning or interpreting experimental work. They unfortunately did not attempt to interpret their own experimental work which the model simulated.

Stolwijk(1971) has subsequently reported on a digital computer model program which is similar to his analogue computer model described above. Unfortunately no results obtained by means of this model have been published so there is no means for assessing the value of the model.

Wissler (1963) extended the dynamic model suggested by the author (Wyndham and Atkins, 1960; Atkins, 1962) from a single cylinder to six elements. Each cylinder is assumed to be homogeneous. The capillary beds of each section are uniformly supplied with arterial blood. The elements are connected by a vascular system and have a common blood pool. Wissler's latest model (Wissler, 1964, 1966) is complex and is designed for a detailed study of the distribution of heat throughout the body. Strangely enough, he does not take notice of the rather critical high non-linear temperature gradient near the skin surface reported by Bazzett (1949), described in Section 2.3 above.

Apart from the fundamental heat transfer analysis, none of the models described above have made any significant contribution to the knowledge of the thermoregulatory process. The dynamic models have merely simulated a few experimental results. In an effort to prove the value of a model as a research tool, the author used the analogue computer simulator to examine the relative importance of the control actions on stabilising the body temperature (Atkins, 1968).

The model is the same as that illustrated in Figure 2.7. Tests were made with control initiated from

a) the core alone;

b) the arterial blood temperature alone;

c) a combination of core and skin temperature, then arterial blood and skin temperature; and

d) the computed mean body temperature.

Various control characteristics were tested by setting up the desired family of curves similar to those illustrated in Figure 2.5, on function generators. Tests were restricted to a resting subject exposed to a variety of ambient temperatures in both heat and cold. A number of analogue computer recordings demonstrated the control actions. The experience gained by the simulator was summarised by six statements:

a) The control of sweat rate by an internal temperature is the most important and powerful mechanism for stabilising the internal body temperature in warm environments.

b) The location of the temperature which initiates control is not critical for resting conditions, control initiated by the arterial temperature produced the most favourable results.

c) Skin temperature does not play an important part in controlling sweat rate in warm resting conditions.

d) Surface blood flow control, which appears to saturate at a moderate ambient temperature, does not change the core temperature of a resting

subject significantly. Its main function is to increase the skin temperature and, therefore, reduce the heat load on the body.

e) Blood flow control is initiated mainly by the core temperature.

f) In a mild cold environment, blood flow is the only form of control. Skin temperature initiates an immediate change in blood flow thus stabilising the core temperature for the first hour. The internal temperature control predominates at a later stage and has a lasting effect on control. Steady state is reached after at least five hours.

Most of these comments are confirmed by analysis in Chapter 5. The analogue model was used to simulate the first series of experiments in the climatic chamber, described in Section 4.10.1. The results are illustrated in Figure 2.8.

The analogue model was subsequently used to test the series 2 and 3 climatic chamber experiments with working men. It was soon apparent that the model was inadequate. After the model had twice been enlarged it was decided to replace the analogue computer with a digital computer simulator which became available at that time. The advantages of a digital computer over an analogue computer are:

a) the ability and capacity of the digital computer to simulate more complex models;

b) a much bigger degree of "reproducibility" and accuracy is possible;

c) the model programs may be used by other computers and it is, therefore, possible for workers to make use of and compare other models with their own.

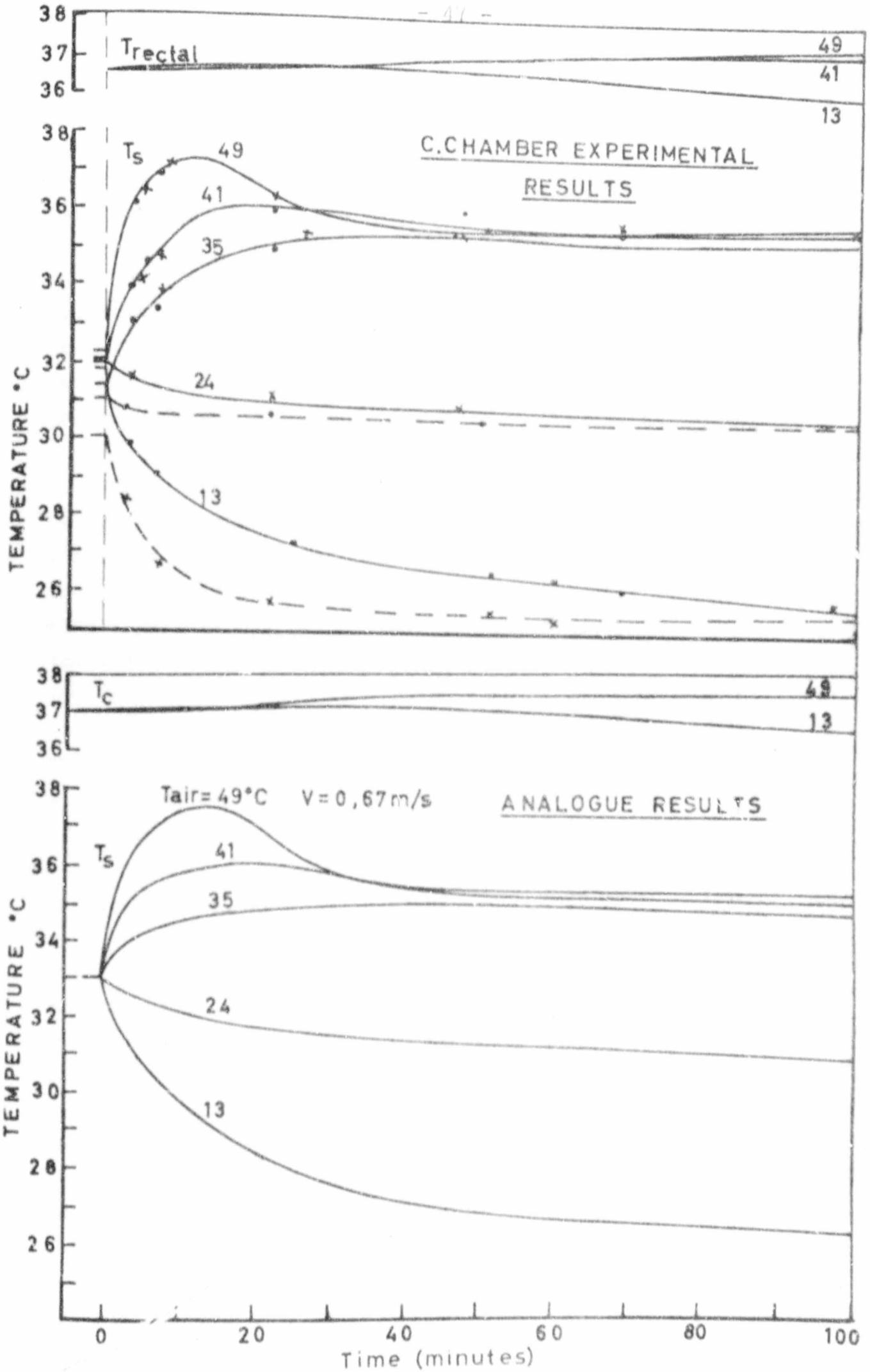

FIGURE 2.8

A comparison between climatic chamber experimental results and the analogue computer records for exposure to various temperatures.

The only disadvantages are slower computing time and higher costs.

The first series of digital computer tests, reported by the author (Atkins and Mitchell, 1971) revealed the need for a change in the peripheral blood flow control mechanism and higher control sensitivity during exercise. The results are discussed in detail in Chapter 7.

There are a few other important models. Hsu, Fan and Hwang (1972) described a steady-state model resembling Wissler's, which is intended specifically for studying thermal gradients within the limbs and torso of the body when a part or all of the body is placed within a temperature regulated jacket.

Hsu (1971) in his doctoral dissertation has compiled the mathematical solutions of the diffusion equation for a number of different thermal models. These include both steady-state and dynamic models of the body which are for studying thermal gradients within the body and provides no information about the control mechanism.

Cornew, Houk and Stark (1967) described a very simple electrical network model consisting of a single conductance and a single capacitance. Their model was confined entirely to a neutral environment where, they claim, the body maintains fine control through vascular convection adjustment. Shivering and perspiration are excluded. Control is initiated from the core temperature. Their analysis of this simple model shows how vascular control, that is, the adjustment of the one conductance, will reduce the body transient time constant.

2.6 Conclusions

It is very evident from the literature that many workers have each made their own small contribution to this very complex problem and that much has been achieved during the last three decades. Progress has been slow as experimental work is difficult and expensive.

The three thermal control actions are clearly established but the source of the control action is not clear. It would seem that both core and skin temperature are involved. Though there is a tendency for heat physiologists to accept the idea of mean body temperature initiating control, there is evidence of the presence of temperature-sensitive regions only in the hypothalamus, spine, abdomen, some veins and the skin. These areas are not sufficient to enable mean body temperature to be predicted. If there are no other thermo-sensors there must be some other form of stimulation during exercise.

There is very little knowledge of the peripheral blood mechanism, particularly very near the skin surface. It would seem from B. Nielsen's results (1969) that the first few millimetres of tissue near the surface determine the major thermal gradient between core and skin.

Models are a useful analytic tool for studying the thermal state of the body. There are essentially two types of models. One gives a detailed account of heat distribution within each of the elements of the body; it is a model of the controlled system. The other is designed primarily for studying the functional characteristics of the thermal control mechanism; it requires a simple model of the controlled system and a model of the controlling system. Most of the work on models has been devoted to the controlled system. It is doubtful whether these models, with all their detail,

are of any practical value at this stage or whether they are truly correct as there is very little detailed experimental evidence to verify the results. There are few thermoregulatory models which have provided useful information concerning either resting or working conditions. Apart from the work of Cornew et al. (1967) who produced a very simple model describing man in a confined environment, there has been no mathematical analysis of the control mechanism.

In reviewing a number of thermoregulation models, Mitchell stated that workers have failed to recognise important physiological facts obtained by experiment (Mitchell, Atkins and Wyndham, 1971). This is partly true; the fact is that no new models have been produced during the past few years. Mitchell et al. suggested a model which takes into account most of the important factors mentioned above. A block diagram ofthe model is illustrated in Figure 2.9.

Cold and warm thermo-sensor signals appear from all parts of the body and terminate in a common central area which provides three resultant control actions for sweating, peripheral vasomotor tone and shivering. There is no reference, or set point temperature, and the central control area is itself temperature sensitive. Exercise provides some additional non-thermal influence on the control action. There is a local surface temperature affect on both sweating and peripheral blood flow. In the latter case there is both modulation and an additive component. The possibility of a rate as well as a proportional control action is not excluded. The model displays some characteristics of parallel-path feedback control which Brown and Brengelman (1971) have observed to occur in almost all biological systems.

A dynamic functional model should be of assistance in answering the objectives given at the end of Chapter 1.

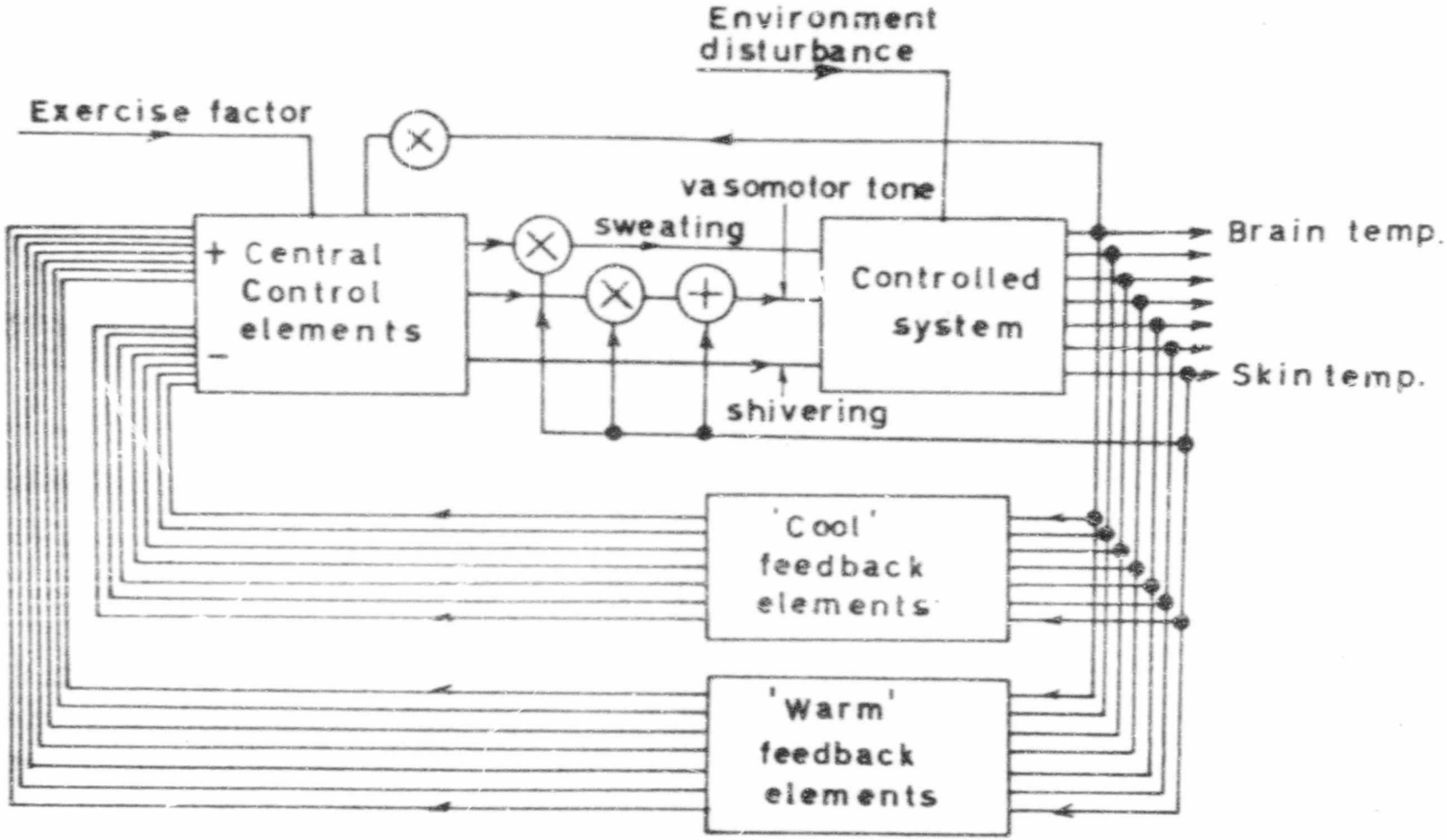

FIGURE 2.9

A block diagram of the suggested short-term thermoregulation system in man.
(Mitchell, Atkins and Wyndham,1971)

CHAPTER 3

AN INITIAL EXAMINATION OF THE THERMOREGULATORY MECHANISM OF THE BODY

3.1 Nomenclature

A_b Surface area of body (m^3)
A_r Effective radiation area of body (m^3)

B_c Multiplication coefficient denoting cardiac output
B_v Multiplication coefficient denoting vasomotor tone

c_b Thermal capacity of blood (J/m^3 °C)
c_n Thermal capacity of segment n (J/m^3 °C)
C_n Thermal capacitance of segment n (J/°C)
C_{hl} Thermal capacitance of heart and lungs (J/°C)

h_b Rate of vascular heat exchange per unit volume of tissue (W/m^3)
h_m Metabolic heat input per unit volume of tissue (W/m^3)
H Rate of heat flow (W)
H_{b_n} Total rate of vascular heat exchange in segment n (W)
H_c Rate of heat loss by convection (W)
H_e Rate of evaporative heat loss (W)
H_n Rate of respiratory heat loss (W)
H_m Rate of metabolic heat production (W)
H_n Total rate of heat gain in segment n (W)
H_r Rate of heat loss due to radiation (W)
H_{rc} Rate of heat loss by radiation and convection (W)
H_w Increase in metabolic heat production due to work (W)

k_{b_1} Constant
k_{ds} Constant representing rate of change of T_s sensitivity
k_{hp} A constant representing thermal sensitivity of the synapses in the hypothalamus
K_n Conductance of segment n (W/°C)
K_{rc} Coefficient of heat exchange for radiation and convection (W/°C)
K_s Coefficient of vascular heat exchange proportional to the surface area of contact between capillaries and tissue (W/°C)

m_n Rate of blood flow entering segment n, per unit volume of tissue (m^3/sec m^3)

M_f Rate of blood flow to fatty tissue (m^3/sec)

M_s Rate of blood flow to skin (m^3/sec)

M_n Rate of blood flow in segment n (m^3/sec)

p Root denoting a pole

P_a Atmospheric pressure (mbar)

r Radius (m)

s Laplace operator

t Time (seconds)

T Temperature (°C)

T_a Air temperature (°C)

T_{ar} Arterial blood temperature (°C)

T_c Core temperature (°C)

T_h Hypothalamic temperature (°C)

T_r Rectal temperature (°C)

T_{rad} Temperature of radiation (°C)

T_s Mean skin temperature (°C)

T_{sp} Spinal cord temperature (°C)

T_v Venous blood temperature (°C)

V Air velocity (m/sec)

V_{BM} Volume of blood in muscle (m^3)

z Root denoting a zero

zc Cold sensor signal

zw Warm sensor signal

Z_b Blood flow control action signal

Z_c Total cold neuro-sensor signal

Z_e Evaporation control signal

Z_m Metabolic control signal

α Specific heat (J/kgm °C)

ρ Density (kgm/m^3)

3.2 The thermoregulatory mechanism and methods of identifying its behaviour

The thermoregulatory mechanism of the body, illustrated in Figure 3.1, comprises two major components, namely, the controlled system representing heat distribution within the body, and the controller which governs the three control actions. There are two dependent variables in the controlled system which can be measured, namely, skin temperature T_s and core temperature T_c represented by the rectal temperature. It is assumed that core temperature is the controlled variable, any deviation of this temperature from a mean value attained when the body is a rest in a comfortable environment, is a thermal strain. Other variables of interest are the muscle, arterial blood, hypothalamus, spine and deep-skin temperatures. Unlike most control circuits, there is no finite reference.

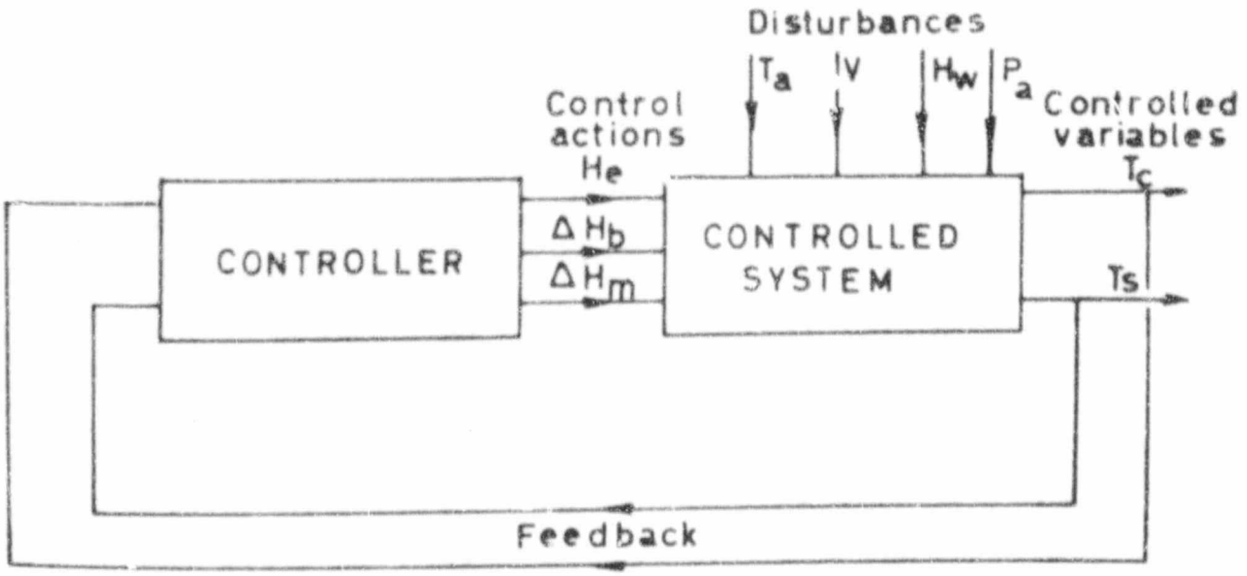

FIGURE 3.1

The thermoregulatory mechanism.

There are four independent variables which, if altered, disturb the thermal equilibrium of the controlled system and cause thermal stress. These are:

a) environmental temperature, T_a, (air temperature is assumed to be equal to the temperature of radiation from the surrounding environment),

b) air velocity, V,

c) physical activity which will increase the rate of heat production due to metabolism by an amount H_w, and

d) the humidity, or water vapour pressure in the air.

The humidity is not regarded as being a serious source of disturbance, but rather a factor which imposes limits on thermal equilibrium.

There are three possible control mechanisms by which the controller can overcome, or minimise, the disturbance of the controlled variable. These are:

a) regulation of loss of evaporative heat, H_e,

b) regulation of the rate of exchange of heat between core and skin by vascular convection, ΔH_b, and

c) regulation of the amount of metabolic heat produced, ΔH_m.

The " Δ " term is used to dencte a change in condition in the latter two actions. Where there is no control action both H_b and H_m have finite values, whereas the value of H_e is virtually zero.

A change in any one or all of the independent variables is a disturbance and will cause the controlled variable to respond. Feedback from T_c, T_s and other variables activate the controller which in turn responds by exerting a control action. The controlled variable and other dependent variables may be expressed as a function of the independent variables and controller actions as

$$T_c(t) = F\left[T_a(t),\ V(t),\ P_a(t),\ H_w(t), H_e(t),\ H_b(t),\ H_m(t)\right] \qquad 3\text{-}1$$

where F denotes function.

The form and the value of the coefficients of this closed loop equation must be determined. The equation is derived from a knowledge of the controller and the controlled system. There is evidence that the characteristics of both the controller (Wyndham and Atkins, 1968) and the controlled system (Mitchell, 1972) are nonlinear. If this is the case, an equation representing the system over the entire range of environments normally encountered by man, would be very complex. An alternative approach is to derive a set of simple linear equations which will relate a change in the dependent variables to a small change in the independent variables. The form of this linear closed loop equation will probably remain the same, but the value of the coefficients will vary with the values of the independent variable, that is with thermal stress.

There are numerous models of the controlled system, as mentioned in Chapter 2. The behaviour of the controller, particularly when the body is not in a state of thermal equilibrium, is not understood. This information is the major objective of this thesis. Both controller and controlled system must be analysed in order to determine the form of the closed loop equation.

The equation is likely to have the form of the typical expression given below.

$$T_c(s) = \frac{G_1(s+z_1)(s+z_2)\ldots(s+z_n)}{(s+p_1)(s+p_2)\ldots(s+p_n)}\,\Delta T_a(s) \qquad 3\text{-}2$$

and

$$T_s(s) = \frac{G_2(s+z_1)(s+z_2)\ldots(s+z_n)}{(s+p_1)(s+p_2)\ldots(s+p_n)}\,\Delta T_a(s) \qquad 3\text{-}3$$

where p and z are constants or the 'roots' of the equation, and which define the time constants of the closed loop system.

G is a constant which defines the final steady state increment $\Delta \overline{T}_c$, and

T_c denotes the transient change in T_c as a result of the small disturbance ΔT_a.

The expression is written in a Laplace transform with 's' denoting the operator. The number of roots in this equation will depend on how detailed one wishes to express the controlled system.

A mathematical analysis of a simple control system is usually sufficient to provide all the information as the system parameters may be estimated from their physical characteristics without the use of special tests. Complex systems with non-linear characteristics require both mathematical analysis and experimental identification. Non-linear characteristics are located by subjecting the system, initially at'steady state', to a series of small excursions and assuming a linear response during each excursion. The experimental work identifies the coefficients of the linear closed loop equation for each excursion. If the value of the coefficients vary for each test then the system is non-linear. The non-linear characteristic of a coefficient is determined from a curve where the various values of the coefficient, derived from the tests, are plotted as a function of the independent or a dependent variable. In some instances the coefficient represents the slope of a line. In this case a curve is made up from a set of straight lines where the slope of each line is given by the value of the coefficient from each test.

Four control engineering identification techniques were considered for determining the characteristics of the controller and the controlled system:

a) analysis of a step disturbance to the system,

b) analysis of a pulse disturbance to the system,

c) analysis of a frequency response test of the system, and

d) observation of a random varying disturbance and the systems response to the disturbance at small equal time intervals over a period of time, and fitting the best characteristic equation by multiple regression.

The step disturbance test is the most convenient for physiological observations. A subject is moved from a particul r environment in one room to a different environment in another room and the temperature response of his body to this sudden change in environment is noted.

This technique is suitable for relatively simple systems or for determining the predominant time constants of more complex systems providing they are linear within the range of examination. The tests will provide the basic information about the thermoregulatory response of man.

A simulation model is very valuable in evaluating a system. It may be used either to

a) check the system which has been identified, by reproducing the experimental results, or

b) to identify the system directly without analysis by a series of logical tests.

Both techniques will be used in this study.

Before proceeding with an account of the experimental identification tests, it is necessary to analyse both the controller and the controlled system, to list the unknowns which require identification and to establish the form of the closed loop transient equation.

3.3 The controller

The controller determines the type of corrective action to be taken following a thermal stress. The magnitude of the action is dependent upon the integrated mean 'signal' resulting from a large number of 'signals' emanating from many temperature sensors. These neuro-sensors are situated in the skin, the hypothalamus, the spine and possibly other parts of the body.

The skin sensors are assumed to be immediately beneath the epidermis and to be distributed evenly throughout the body. The hypothalamus contains a number of sensors. The hypothalamic temperature is assumed to be equal to the arterial blood temperature as it is well supplied with arterial blood and is separated from the thermal mass of the trunk. The spinal temperature will be represented by the core temperature.

Figure 3.2 illustrates the stages between the input temperature signal and the output action of the controller. It is not essential to know the characteristics of each stage if the overall characteristics are required. The controller may be treated as a'black box'. However, an examination is made of the neuro-integrating centre as it provides some information about the inter-relationship between the temperature sensors and the control actions.

A model similar to that suggested by Bligh (1972) and described in Chapter 2, will serve as a basis for the analysis. (Refer to Figure 3.3)

All warm sensors are assumed to terminate together to form a combined representative 'warm signal', Z_w. Similarly, the cold sensors form the 'cold signal', Z_c. Therefore

$$Z_w = \Sigma(zw)_h + \Sigma(zw)_s + \Sigma(zw)_{sp} + \ldots \qquad 3\text{-}4$$