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A study of temperature control in the human body by experiment and computer simulation

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2014-10-15
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It is the initial steady state value of H_b or R_b which is required, any further change in H_b is taken into account by the term ΔH_b which is a function of T_c and T_s, equation 5-7.

The value of R_{rc} ($= 1/K_{rc}$) is given equation 3-28, namely

$$K_{rc} = (6{,}02 + 8{,}28(P_a/1013)^{0{,}6}\ V^{0{,}6})A$$
$$= 20{,}1\ W/^{\circ}C \text{ for } V = 0{,}67\ m/s. \qquad 5\text{-}32$$

The total thermal capacitance of the body , $C_c + C_s$, may be calculated from a knowledge of the weight of the subject and the specific heat of tissue. Since the specific heat of blood is similar to that of tissue it is not necessary to separate the blood from the tissue in this study.

Therefore

$$C_c + C_s = \text{subject weight x specific heat}$$
$$= 207\ 000\ J/^{\circ}C \quad \text{(refer to Table 3.1)} \qquad 5\text{-}33$$

The value of C_s may be calculated from a knowledge of the initial slope of the skin temperature transient. The initial slope at time $t = 0_+$ is determined from equation 5-24 and is given by

$$\frac{dT_s}{dt} = -\alpha a_s - \beta a_s \qquad 5\text{-}34$$

Assume for the moment that the values of A_{ed} and A_{bd} are small (this is confirmed later), then according to Appendix A4,

$$\frac{dT_s}{dt} = \frac{1}{R_{rc} C_s} \qquad (\text{for } t = 0_+) \qquad 5\text{-}35$$

Since the air velocity is constant, the value of C_s is given by

$$C_s = \frac{1}{R_{rc} \dfrac{dT_s}{dt}} \qquad (\text{for } t = 0_+) \qquad 5\text{-}36$$

Table 5.1 lists calculated values of dT_s/dt and C_s taken from the transient curves illustrated in Figures 4.16 or 5.1. A comparison is made of the initial slope of each skin temperature curve for three different values of air temperatures

and air velocities. The calculated value of the slope is based upon that of a normalised curve, that is, account is taken of the amplitude of each step change in air temperature. It may be seen that the slope is dependent upon air velocity and that the calculated value of C_s is relatively constant.

Therefore $C_s = 28\ 654 \approx 28\ 500$ J/°C 5-37

and $C_c = 207\ 000 - 28\ 500$

$= 176\ 500$ J/°C 5-38

TABLE 5.1

A summary of a few measurements taken from the first series of experiments

Air temp. (°C)	Air veloc. (m/s)	Settling time (minutes)	Slope of T_s (°C/sec)	R_{rc} (°C/W)	C_s (J/°C)
35	0,67	90-100	0,000 85	0,05	23 530
	3,11	75-90	0,000 1	0,028	32 500
40,5	0,67	65	0,000 62	0,05	32 300
	1,86	57	0,000 94	0,035	30 395
	3,11	54	0,001 3	0,028	27 500
49	0,67	70	0,000 68	0,05	29 411
	3,11	50	0,001 2	0,035	23 800
	3,11	48	0,001 2	0,028	29 800
			Mean value of C_s		28 654
			Standard deviation		3 467

It is important to understand how the control coefficients influence the response of the system before determining the best method of identifying the coefficients.

In order to clarify this study, the predominant source of control (Atkins and Wyndham, 1969), that is the components of the control action which are initiated from the core, A_b and A_e, are studied first. The response of the model to varying values of A_b and A_e is examined by analysis and by computer simulation. The computer simulation of the model demonstrates that when control is initiated from the core alone, the model can reproduce the steady state experimental temperatures, but, it can not reproduce the transient temperature response of man.

The four coefficients, A_b, A_{bs}, A_e and A_{es} are identified in the second study. The model is then analysed in order to examine the importance of control initiated from the skin.

The skin temperature multiplication term, which represents the sensitivity of the ' neuro - motor'to temperature (equation 3-12) is examined in the third study. Finally, the rate control coefficients, A_{bd} and A_{ed} are examined.

5.4.1 Proportional control initiated from the core temperature.

In this section the control action components initiated only by the core temperature are examined. The control actions are denoted by

$$H_e = (T_c - T_t)A_e \qquad 5\text{-}39$$

and

$$\Delta H_b = (T_c - T_t)\, A_b \qquad 5\text{-}40$$

The transient expressions for T_c and T_s, taken from equations 5-7 and 5-8, with A_{bs}, A_{bd}, A_{es} and $A_{ed} = 0$, are therefore given by

$$\frac{\Delta T_c(s)}{\Delta T_a(s)} = \frac{1}{s^2(R_{rc}R_bC_cC_s) + s((R_{rc}+R_b)C_c + R_{rc}C_s(1+R_bA_b)) +}$$

and

$$\text{contd. } 1 + R_{rc}A_e + R_bA_b \qquad 5\text{-}41$$

$$\frac{\Delta T_s(s)}{\Delta T_a(s)} = \frac{sR_bC_c + (1+R_bA_b)}{s^2(R_{rc}R_bC_cC_s) + s(R_{rc}+R_b)C_c + R_{rc}C_s(1+R_bA_b)) +}$$

$$\text{contd. } 1 + R_{rc}A_e + R_bA_b \qquad 5\text{-}42$$

$$G_1 = \frac{1}{R_{rc}R_bC_cC_s} \qquad 5\text{-}43$$

$$G_2 = \frac{1}{R_{rc}C_s} \qquad 5\text{-}44$$

$$\gamma_2 = (1 + R_bA_b)/(R_bC_c) \qquad 5\text{-}45$$

$$Q = \frac{(R_{rc}+R_b)C_c + R_{rc}C_s(1+R_bA_b)}{R_bR_{rc}C_cC_s} \qquad 5\text{-}46$$

$$R = \frac{1 + R_bA_b + R_{rc}A_e}{R_{rc}R_bC_cC_s} \qquad 5\text{-}47$$

The influence of the sensitivity of the control of sweat rate and blood flow, A_e and A_b, on the response of the body are now examined.

The time constants of the two exponential components in equations 5-23 are the same as those in equation 5-24. Their values are given by

$$\tau_\alpha = 1/\alpha \quad \text{(see 5-20)} \qquad 5\text{-}48$$

$$\tau_\beta = 1/\beta \quad \text{(see 5-21)} \qquad 5\text{-}49$$

Since the thermal gradient is near the skin surface, C_c is much greater than C_s and, therefore, τ_β is much greater than τ_α.

When a control action does occur, that is, when A_e and A_b are greater than zero, the large time constant, τ_β, will

decrease considerably and the small time constant will increase slightly (refer to equations 5-20,5-21,5-46 and 5-47). The change in the value of the time constant is due mainly to an increase in the value of R (equation 5-47) which, in turn, results in a decrease of the square root term in equations 5-20 and 5-21.

Since A_b appears in both the Q and R components, equations 5-46 and 5-47, A_b has less influence than A_e in reducing the time constant τ_β.

Although the 'settling time' of a system is not clearly defined, it is a more valuable term of reference than the time constants of a system, if the system has more than one time constant. For the purpose of this study 'settling time' is defined as the time taken for a transient to reach and remain within 10 per cent of its final value. Figure 5.4 shows how the settling time of the model is reduced as the value of sweat control sensitivity is increased. Note that the settling time of a passive body in still air is many hours.

If the control gain is increased to a certain value (A_e = 150) the time constants become equal and the square root term of equations 5-20 and 5-21 is zero. This condition is called critical damping, that is

$$Q^2 = 4R$$

or

$$Q/2\sqrt{R} = 1 \qquad 5\text{-}50$$

Larger values of control gain cause the damping coefficient $Q/2\sqrt{R}$, to decrease. Conjugate roots occur in the closed loop equation and there is an 'overshoot' or damped oscillatory response to a disturbance. The larger the value of the control gain, the less damping and the longer the oscillatory response.

The transient response of the skin and core temperatures following a unit step change in air temperature, and calculated from equations 5-23 and 5-24 are illustrated in

contd. page 144

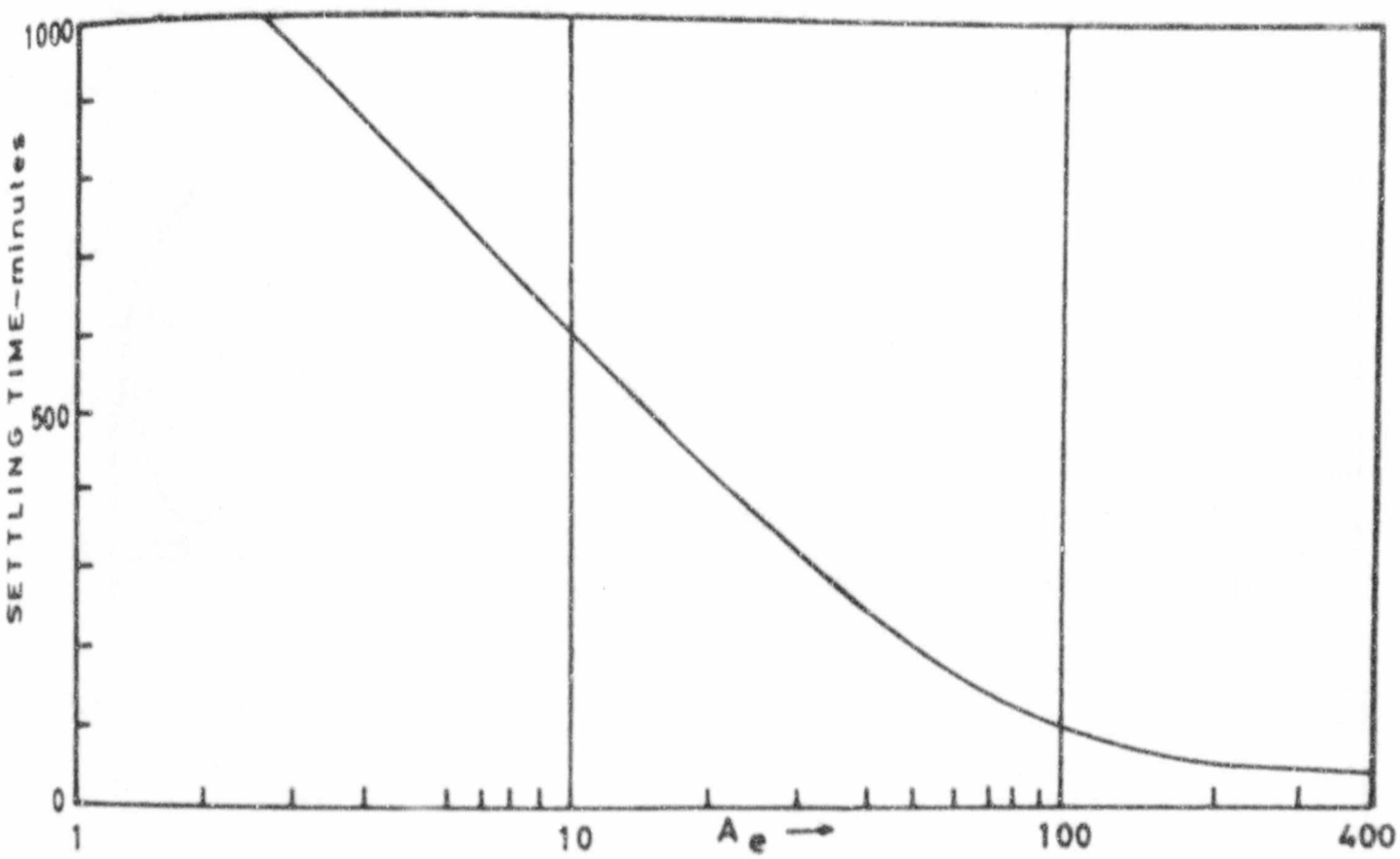


FIGURE 5.4

The influence of sweat control gain on settling time.

Figures 5.5 and 5.6. It is important to note that the curves refer to a unit step change in temperature, and therefore, the temperature scales are relative to the change in air temperature. Figure 5.5 shows the influence of sweat control gain on the reduction of the changes in core and skin temperature. Five curves representing five values of sweat control gain, ranging from 0 to 350 W/°C, are illustrated. The largest value of A_e is equal to the slope of the evaporative heat loss curves given by Wyndham and Atkins (1968).

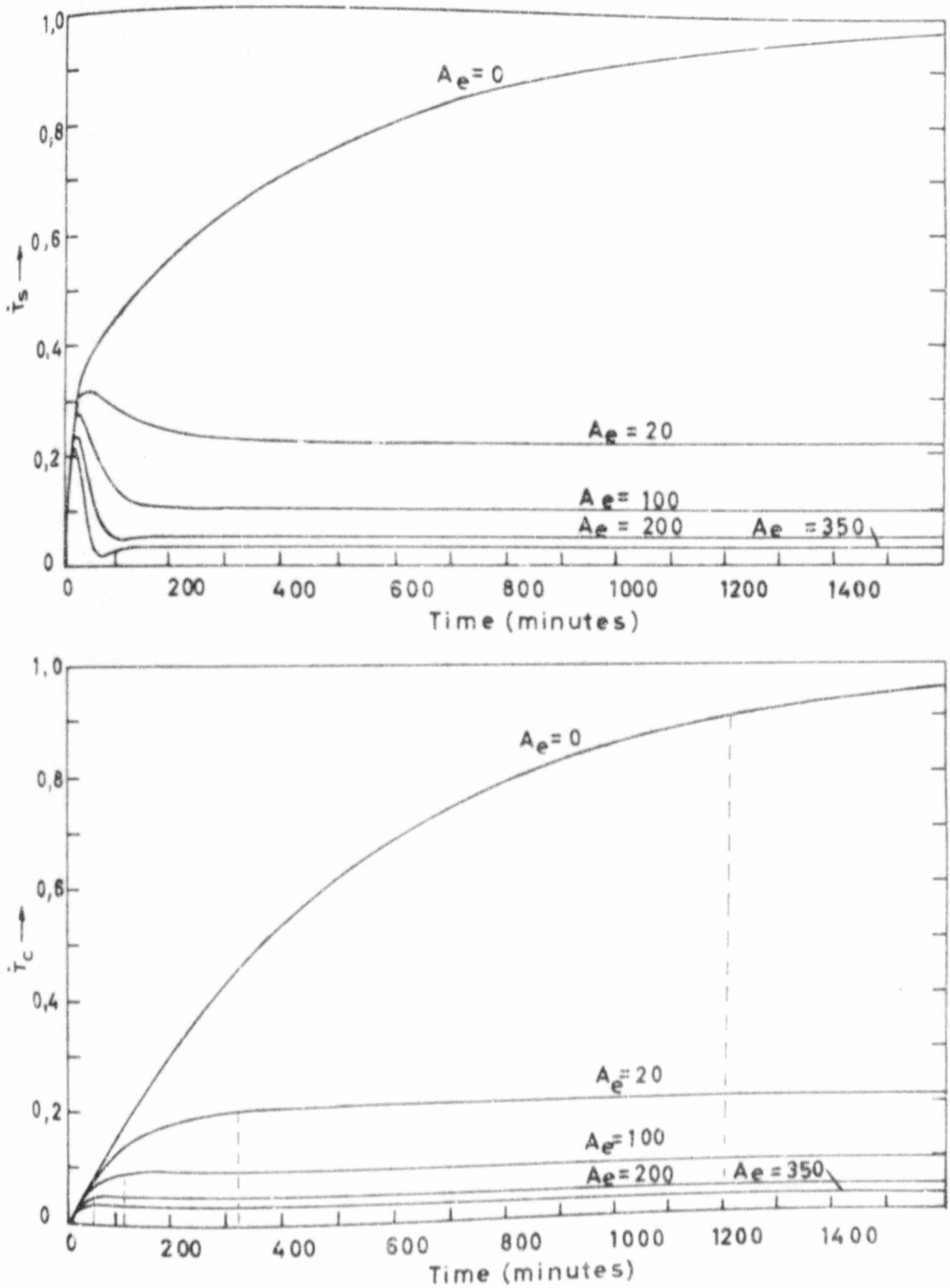


FIGURE 5.5

Transient characteristics of the model for a unit step change in air temperature. The records show five values of $A_e, A_b = 0$.

The broken vertical lines in the lower graph of Figure 5.5 mark the settling time.

The models response demonstrates that the steady state temperature increments, the settling time and the damping factor are reduced by the evaporative control action. There is a noticeable overshoot in the skin temperature transient as the value of A_e is increased.

The first overshoot in the positive direction of the skin temperature transient does not indicate an underdamped control variable. The peak is dependent upon the time constants (α and β) and the amplitude coefficients (a_3 and a_4) of the two exponential terms in equations 5-23 and 5-24. A peak value of $\Delta T_s(t)$ occurs if, and when the derivative of equation 5-24 is zero, that is when

$$\frac{dT_s(t)}{dt} = a_3\alpha e^{-\alpha t} + a_4\beta e^{-\beta t} = 0 \qquad 5\text{-}51$$

or when the two exponential terms have equal amplitude and opposite signs. Critical damping occurs before a second overshoot in the negative direction of the skin temperature transient or a positive overshoot in the core temperature transient. The two runs represented by A_e = 300 and A_e = 350 show an underdamped response.

Figure 5.6 illustrates the influence of the blood control action on the reduction of the values of the skin and core temperature disturbances. Note that both temperature axes have been expanded; the change in either of these temperatures refers to a unit change in air temperature. In this example the sweat rate control gain is constant and is equal to 100 W/°C. Five values representing five values of peripheral blood flow control gain, A_b, are shown. The largest value of A_b was chosen by increasing this value arbitrarily until the records were similar to the experimental results.

When A_b = 0, the steady state increments, $\bar{T}_c$ and $\bar{T}_s$, are equal. As the blood flow control gain is increased, the

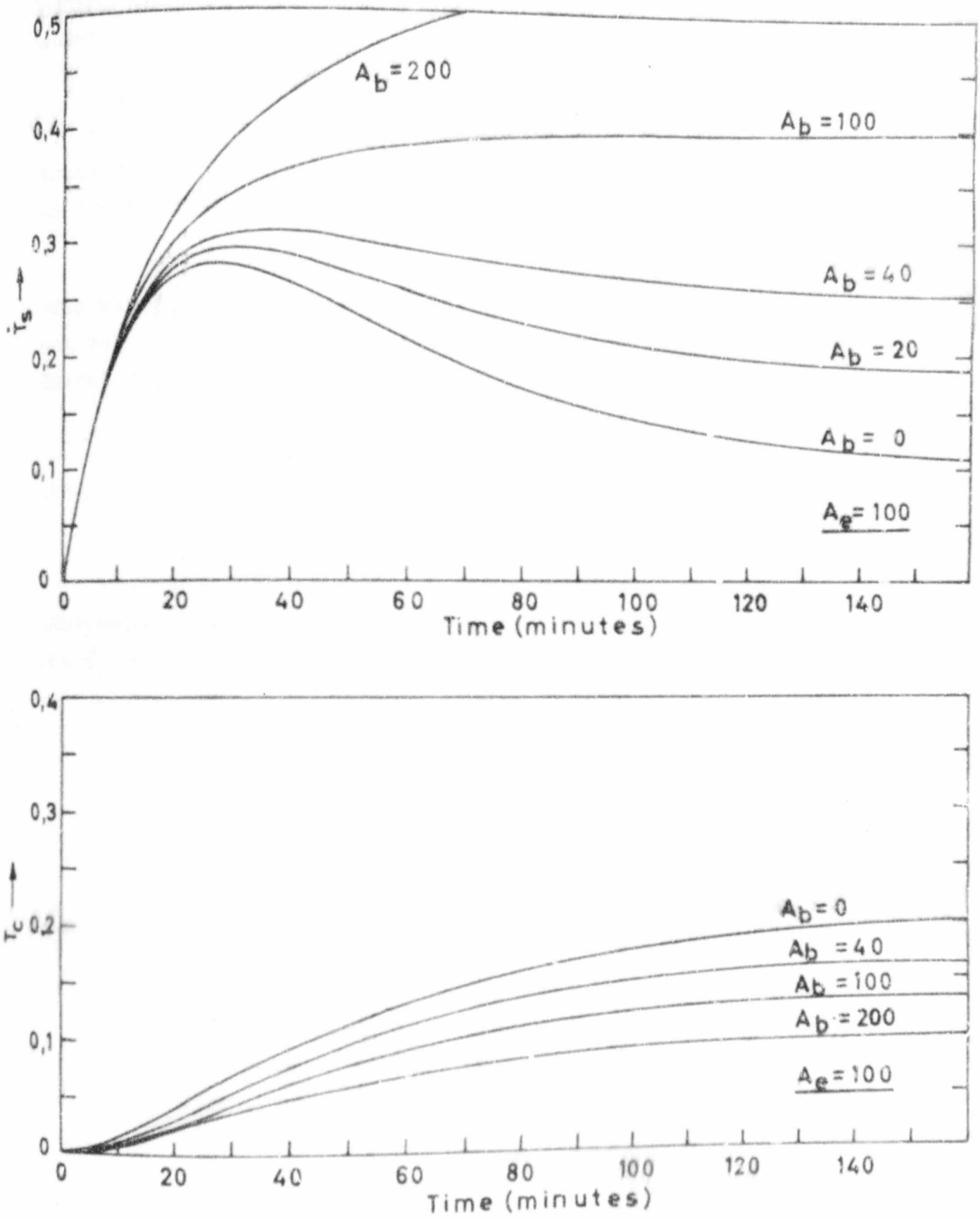


FIGURE 5.6

Transient characteristics of the model for a unit step change in air temperature. The records illustrate five values of blood flow control gain, A_b. The sweat control gain has a constant value of 100 W/°C.

steady state increment $\bar{T}_c$ is reduced while $\bar{T}_s$ increases.

The transient records illustrated in Figures 5.5 and 5.6 confirm that the initial slope of the skin temperature transient is not influenced by changes in either A_e or A_b as the records overlap during the first 10 to 15 minutes.

The incremental steady state temperatures may be determined from the coefficients a_1 and a_4 of equations 5-23 and 5-24 when $t = 0$, or from 5.41 and 5.42 when $s = 0$. Therefore,

$$\bar{T}_c = \frac{1}{1 + A_b R_b + A_e R_{rc}} \bar{T}_a \qquad 5\text{-}52$$

and

$$\bar{T}_s = \frac{1 + A_b R_b}{1 + A_b R_b + A_e R_{rc}} \bar{T}_a \qquad 5\text{-}53$$

The influence of control gain on the steady state increments may be predicted from equations 5-52 and 5-53. Let $\bar{T}_a = 1$.

1) If A_b and $A_e = 0$, then $\bar{T}_c$ and $\bar{T}_s = 1$. (With no control, the change in skin and core temperatures will be equal to the change in air temperature.)

2) If $A_b = 0$ and $A_e \gg 1$, then $\bar{T}_c$ and $\bar{T}_s$ are equal and $\ll 1$. (With only evaporative control, the core and skin temperature increments are equal, and much smaller than the change in air temperature.)

3) If A_b and $A_e \gg 1$, then $\bar{T}_s$ is quite large because of the term $A_b R_b$ in the numerator of equation 5-53. The increment $\bar{T}_c$ will be even smaller than in the previous case due to the additional term A_b in the denominator of 5-53. (With both evaporative and blood flow control, the skin temperature increment is quite large while the core temperature increment is even less.)

It is possible to express A_e and A_b in terms of $\bar{T}_c$ and $\bar{T}_s$ from equations 5-52 and 5-53 as follows.

$$A_b = \frac{N\bar{T}_s - N\bar{T}_c}{N\bar{T}_c} K_b \qquad 5\text{-}54$$

and

$$A_e = \frac{1 - N\bar{T}_s}{N\bar{T}_c} K_{rc} \qquad 5\text{-}55$$

where N refers to a normalised temperature increment.

Figure 5.7 illustrates the steady state incremental change in T_c plotted against sweat control gain for a unit change in air temperature. The three curves represent three values of blood flow control gain. The figure shows that the increase in peripheral blood flow control has relatively little influence on $\bar{T}_c$ in a typical warm condition where the value of A_e is approximately 350. The core temperature increment is less than one-tenth of the change in air temperature.

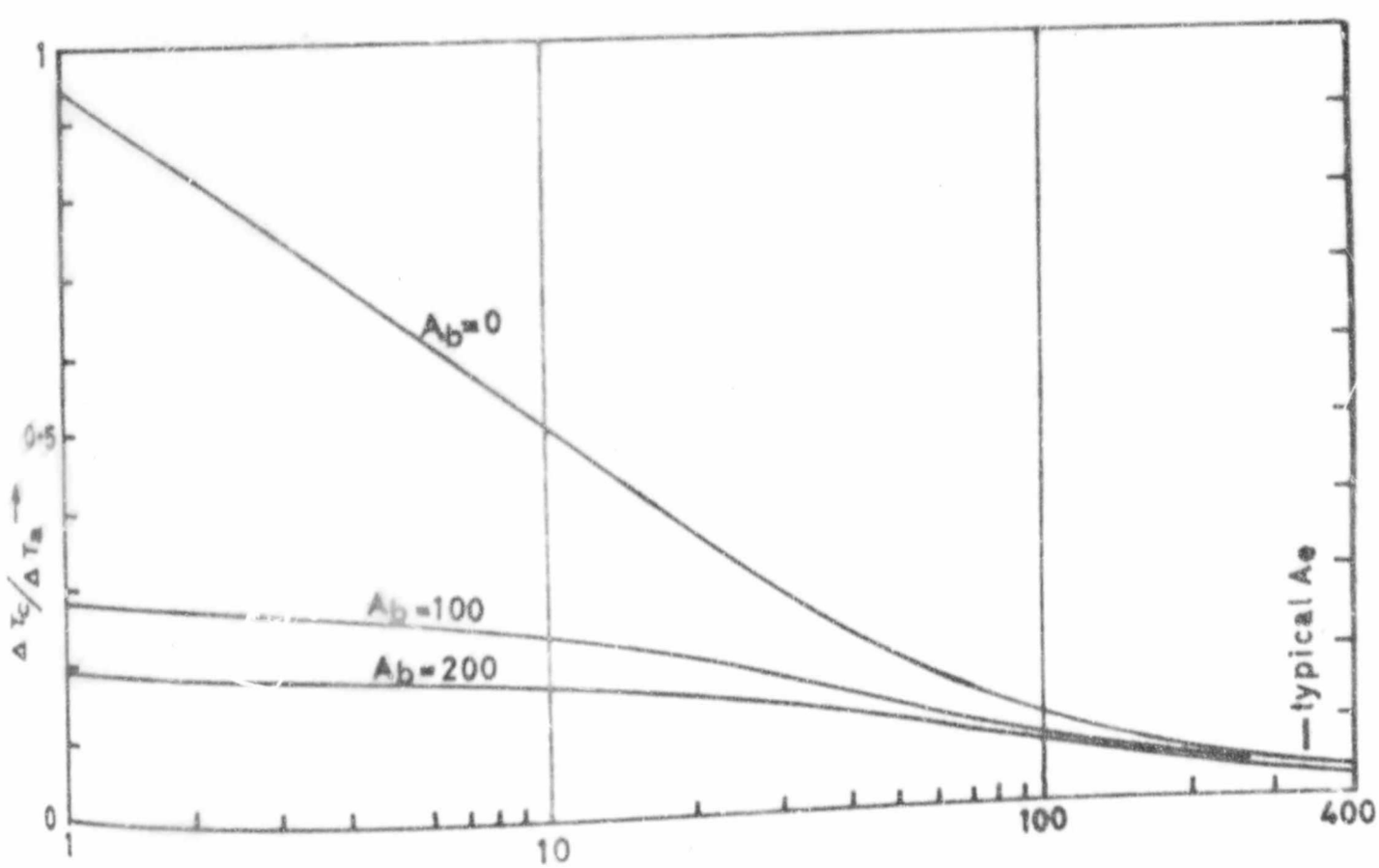


FIGURE 5.7

The influence of sweat control gain, A_e, on ΔT_c.

In summary, the analysis has shown that

1) The control actions reduce the value of the long time constant and hence the settling time of the closed loop system.

2) The sweat control action reduces the incremental steady state change in both skin and core temperatures while the peripheral blood flow control action reduces the core temperature and increases the skin temperature increment.

3) The transient temperature response, that is , the peak value of the T_s and the damping factor are determined by the value of A_b and A_e.

The coefficients A_b and A_e (assuming that A_{bs}, A_{bd}, A_{es} and A_{ed} are zero) may be determined from one of the above three observations. The fact that A_e has the opposite effect to A_b on the value of $\bar{T}_s$, provides a convenient method of determining A_b and A_e.

Consider the steady state relationship given by equations 5-54 and 5-55. The coefficients A_b and A_e may be calculated from the steady state values of T_r and T_s given in Table 4. 9 . The results are listed in Table 5.2.

It is clear that neither control is linear as the values of A_b and A_e vary with temperature, or heat stress. The evaporative control gain increases with temperature while there is a sudden decrease in the value of A_b once the rectal temperature exceeds 37,15°C. The control characteristics, that is the relation between K_b and T_c and the relation between H_e and T_c may be determined from the values of A_b and A_e.

The steady state values of K_b are given in Table 5.2 and plotted as a function of rectal temperature in Figure 5.8. The figure shows that the physiological conductance is constant once the rectal temperature exceeds 37,15°C. Figure 4.15 shows that this condition occurs when a resting

TABLE 5.2

A summary of the mean steady-state skin and rectal temperatures, obtained from Figure 5.15 which are used to compute the control gains A_b and A_e and the physiological conductance K_b. ΔT and $N\Delta T$ refer to a change and a normalised change in temperature respectively.

T_a	T_s	T_c	ΔT_s	ΔT_c	ΔT_a	NT_s	NT_c	A_b	A_e	K_b
28	31,9	36,75								16,5
32,5	34,3	37,0	2,4	0,25	4,5	0,533	0,055	147	162	29,6
35	35,1	37,15	0,8	0,15	2,5	0,32	0,06	128	227	39,02
37,5	35,25	37,25	0,15	0,1	2,5	0,06	0,04	10,5	470	40,0
40,5	35,37	37,35	0,12	0,1	3,0	0,04	0,033	8,0	582	40,4
43	35,46	37,42	0,09	0,07	2,5	0,036	0,028	11,5	691	40,8
46	35,56	37,5	0,1	0,08	3,0	0.033	0,027	9,1	744	41,2
49	35,65	37,58	0,09	0,08	3,0	0,033	0,027	4,5	744	41,4

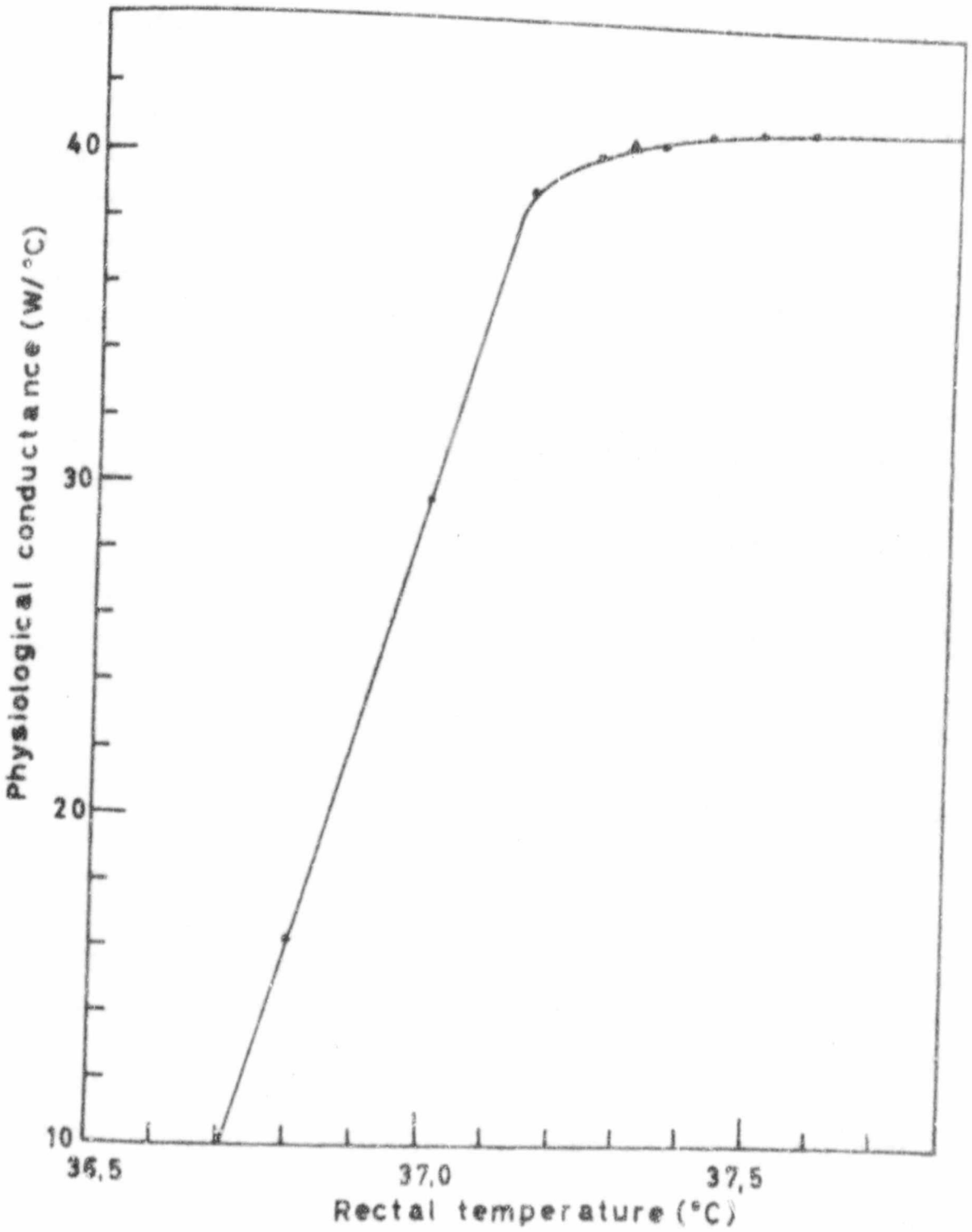


FIGURE 5.8

The steady-state relation between physiological conductance and rectal temperature. The curve represents the mean of of the experimental results.

man is exposed to an ambient temperature in excess of 34°C. The temperature gradient between the rectum and the skin is constant.

This is a very important condition, it was noticed in the first series of experiments (Mitchell et al., 1968). The author suggested that it could be due to the 'saturation' of the vaso-motor tone. The condition is discussed later in the text; for the purpose of this study one must accept that K_b is constant and the value of A_b is small once the rectal temperature exceeds 37,15°C.

The evaporative control characteristics can be constructed from a set of straight lines the slopes of which are given by the values of A_e, or it can be determined from experimental values of H_e. The experimental values can be either direct measurements of evaporative heat loss or values calculated from the steady state equation representing heat balance.

$$H_e = H_m - H_h - H_{rc} \qquad 5\text{-}56$$

Figure 5.9 illustrates the evaporative control characteristics. The solid line drawn through the small points is derived from calculated values of H_e (equation 5-56) using the mean data from Series 1,2,3 and 4 experiments. Four mean experimental values of the direct measurement of evaporative heat loss at four ambient temperatures, taken from Table 4.1C, are shown by the four circles. The calculated values of A_e, given in Table 5.2, are checked by comparing a few values with the slope of the curve. The broken line represents the data for the Series 4 experiment and shows that these subjects have a higher sensitivity than the others. They were probably better acclimatised.

The model is used now to check the analysis of the control mechanism. The response of the model to a step change in air temperature is compared with the experiments made on subjects in the climatic chamber. The response is calculated with a digital computer by solving the differential equations describing the model. The procedure is given in Appendix 6 . The

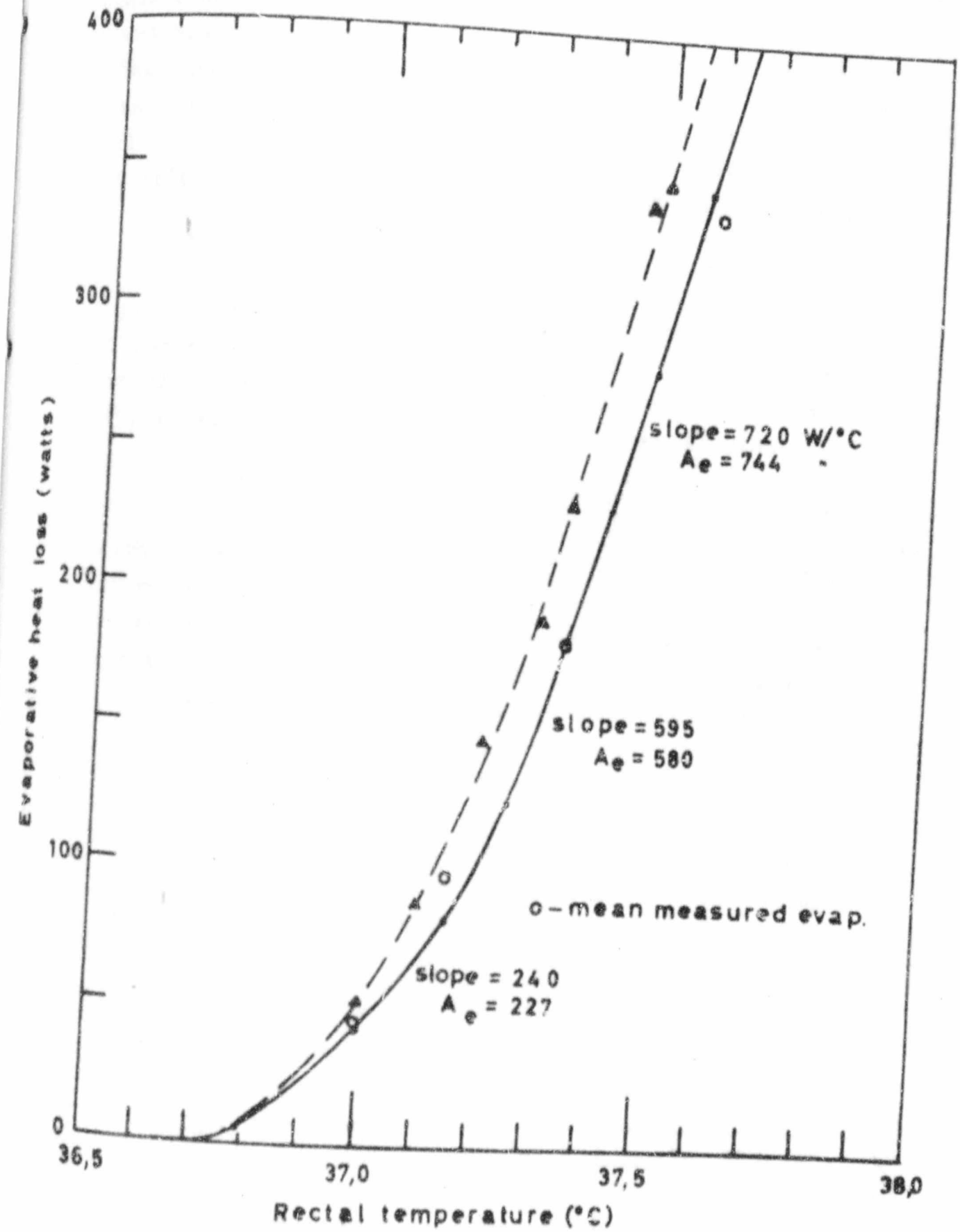


FIGURE 5.9

The steady-state relation between the calculated value of evaporative heat loss and rectal temperature. Four experimental measured values of evaporative heat loss are by circles on the graph. The broken line represents the Series 4 experiment.

non-linear control characteristics, given in Figure 5.8 and 5.9 are approximated by sets of five straight lines. The experiment records illustrated in Figure 5.1 are chosen as a source of comparison in preference to the small step changes in air temperature as it is important to test the complete non-linear range of the control characteristics.

The transient recordings of the model which was tested with the same set of ambient conditions as men in the climatic chamber, were plotted by a computer and are illustrated in Figure 5.10. The record of the experimental results obtained in the climatic chamber, taken from Figure 4.16 are superimposed on the computer plot.

The steady-state values of the model, taken from Figure 5.10 are listed in Table 5.3, they compare favourably with the experimental results. The transient skin temperature peaks differ considerably, particularly in the case of the highest air temperature where there is a large overshoot and damped oscillation. This result was expected as the analysis had shown that conjugate roots will occur if the value of A_e is greater than 150. The settling time for the core temperature of the model is less than the settling time for the experimental rectal temperature. The peak value of the skin temperature transient can be reduced by increasing the value of A_e; this change will, however, cause less damping and will alter the steady state value of T_s and T_c.

TABLE 5.3

A comparison between the mean experimental steady state results, E, and the model steady state measurements, M.

T_a		T_s	T_c	H_e	K_b
35	E	35,1	37,15	80	39
	M	35,2	37,16	78	40,6
40,5	E	35,4	37,35	182	40,6
	M	35,4	37,35	182	40,6
49	E	35,65	37,58	348	41
	M	35,65	37,6	325	40,6

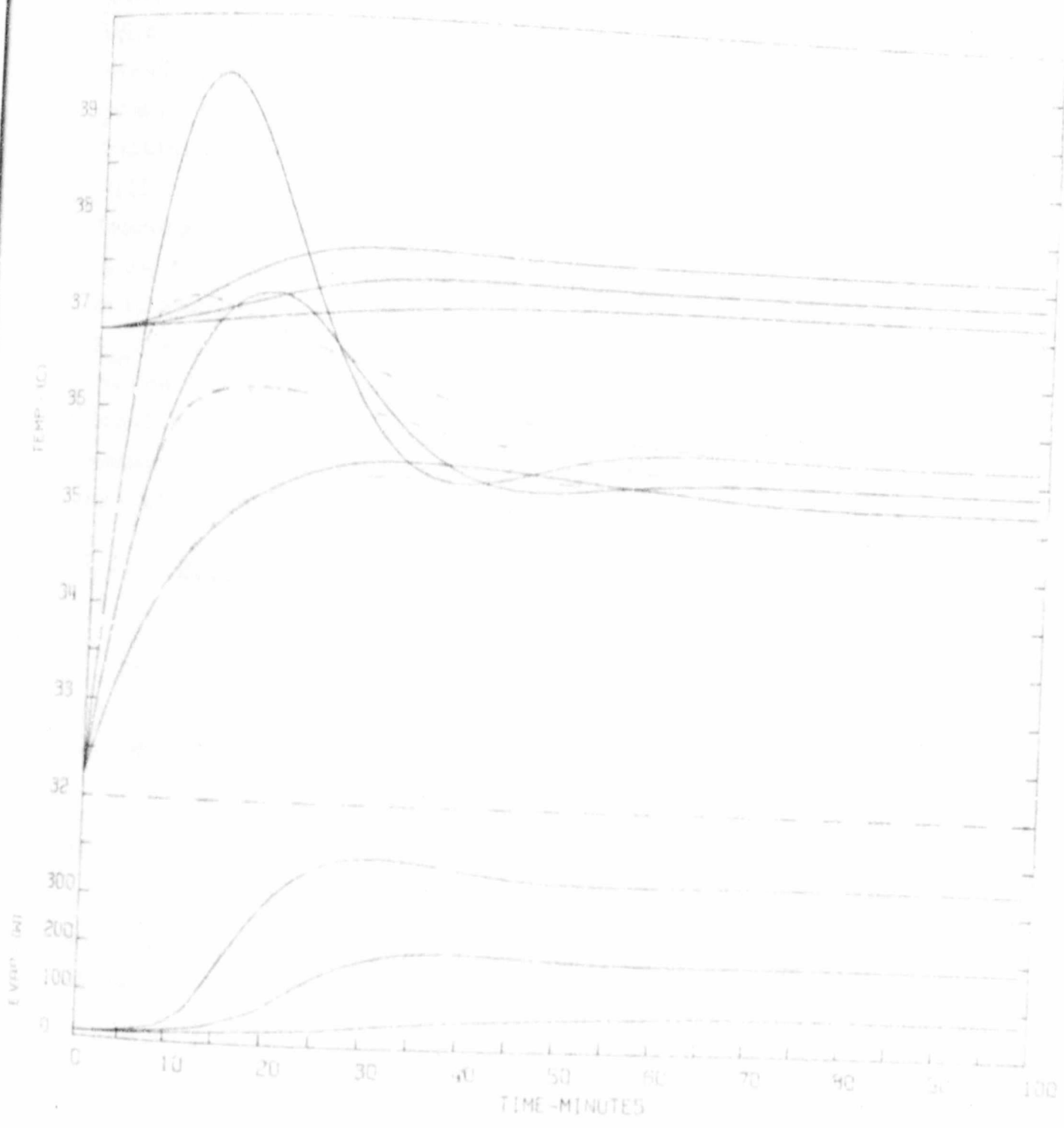


FIGURE 5.10

A computer plot of the models response to a step change in air temperature from 28°C to 35°C, 40,5°C and 49°C; V = 0,67 m/s. Control is initiated from the core temperature alone. The core temperature in temperature and evaporative heat loss records are shown. The broken lines represent the superimposed experimental records.

The results of this study show that either the steady state or the transient response can be reproduced, depending upon whether the control characteristics are derived from steady state or transient data, respectively. It is not possible to reproduce both states with a control which is initiated only by the core temperature. The same condition will apply if the control is initiated only by the skin temperature. Clearly, the control is initiated by the core temperature and another source whichis probably the skin temperature. The skin temperature control component, A_{es}, will initiate sweating sooner and it will therefore reduce the peak value of T_s. The influence of this additional control component on the response of the model is examined and the four coefficients, A_b, A_{bs}, A_e and A_{es} are identified in the next study.

5.4.2 Proportional control initiated from the core and the skin temperatures

In this section the control action components initiated by the core and skin temperature components are examined. The control actions are denoted by

$$H_e = (T_c - T_t)A_e + (T_s - T_{ts})A_{es} \qquad 5\text{-}57$$

and

$$\Delta H_b = (T_c - T_t)A_b + (T_s - T_{ts})A_{bs} \qquad 5\text{-}58$$

where A_{es} and A_{bs} represent the sensitivity of the evaporative and blood flow control actions to skin temperature.

The four control coefficients requiring identification are A_e, A_{es}, A_b and A_{bs}. The values of the coefficients A_b and A_e, which were derived in the previous section, do not necessarily apply to this section.

The transient expressions for T_c and T_s, taken from equations 5-8 and 5-9, (Figure 5.3) are

$$\frac{\Delta T_c(s)}{\Delta T_a(s)} = \frac{1 - R_b A_{bs}}{s^2 R_b R_{rc} C_c C_s + s\,(R_b + R_{rc} + R_b R_{rc}(A_{es} - A_{bs}))C_c +}$$

$$\text{contd.}\quad (R_{rc} + A_b R_b R_{rc})C_s + 1 + A_e R_{rc} + A_b R_b + A_{es} R_{rc} + R_b R_{rc}(A_b A_{es} - A_e A_{bs}) \qquad 5\text{-}59$$

and

$$\frac{\Delta T_s(s)}{\Delta T_a(s)} = \frac{R_b C_c s + (1 + R_b A_b)}{s^2 R_b R_{rc} C_c C_s + s\,(R_b + R_{rc} + R_b R_{rc}(A_{es} - A_{bs}))C_c +}$$

$$\text{contd.}\quad (R_{rc} + A_b R_b R_{rc})C_s + 1 + A_e R_{rc} + A_b R_b + A_{es} R_{rc} + R_b R_{rc}(A_b A_{es} - A_e A_{bs}) \qquad 5\text{-}60$$

These expressions and their numerical solutions retain their 'second- order' form. Only the coefficients a_1 to a_6, α, β and γ differ because of their additional terms containing A_{es} and A_{bs}. The terms G_1, G_2, Q and R, which determine the coefficients and hence the roots, (refer to equations 5-14 to 5-19), are now expressed as

$$G_1 = \frac{1 - R_b A_{bs}}{R_b R_{rc} C_c C_s} \qquad 5\text{-}61$$

$$G_2 = \frac{1}{R_{rc} C_s} \qquad 5\text{-}62$$

$$Q = \frac{(R_{rc} + R_b)C_c + R_b R_{rc}(A_{es} - A_{bs})C_c + R_{rc} C_s (1 + R_b A_b)}{R_b R_{rc} C_c C_s} \qquad 5\text{-}63$$

$$R = \frac{1 + R_{rc}(A_e + A_{es}) + R_b A_b + R_b R_{rc}(A_b A_{es} - A_e A_{bs})}{R_b R_{rc} C_c C_s} \qquad 5\text{-}64$$

The steady state increments, $\overline{T}_c$ and $\overline{T}_s$, are given by

$$\overline{T}_c = \frac{1 - R_b A_{bs}}{1 + R_{rc}(A_e + A_{es}) + R_b A_b + R_b R_{rc}(A_b A_{es} - A_e A_{bs})}\ \overline{T}_a \qquad 5\text{-}65$$

and

$$\overline{T}_s = \frac{1 + R_b A_b}{1 + R_{rc}(A_e + A_{es}) + R_b A_b + R_b R_{rc}(A_b A_{es} - A_e A_{bs})}\ \overline{T}_a \qquad 5\text{-}66$$

Since there are now four coefficients, both transient and steady state data are required for identifying these coefficients.

The evaporative heat loss is made up from two control components which are initiated from T_c and T_s. The influence of the latter component on the transient response of the system may be determined from equations 5-63 and 5-64 or from a 'root locus' plot of the closed loop equations. The 'root locus' plot is illustrated in Figure 5.11. The locus represents the roots of equation 5-59 for various values of A_{es} ranging from 0 to 100. The values of A_e and A_b are 350 and 0 respectively and the value of K_b is the maximum value of 40 W/°C. This curve therefore applies to the range of ambient temperature above 34°C. The broken line represents the same range ofvalues of A_{es}, the values of A_e, A_b and Kb are 200,150 and 20 respectively. This curve applies to an ambient temperature in the region of 32,5°C.

If A_{es} is zero, conjugate roots occur. An increasing value of A_{es} increases damping and eliminates the conjugate roots. The larger time constant is increased and therefore the settling time is increased. The skin temperature control component will therefore stabilise the control action and reduce the peak value of T_s.

The calculated steady state value of physiological conductance, K_b, given in Table 5.2, and the Figure 4.15 shows that the physiological conductance is almost constant in the case of a resting man in an ambient temperature above 34°C. One can assume, therefore, that the values of A_b and A_{bs} are small, or negligible, in this region. With this assumption it is possible to re-write equation 5-66 so that

$$N\bar{T}_s = \frac{\bar{T}_s}{\bar{T}_a} = \frac{1}{1 + R_{rc}(A_e + A_{es})} \qquad 5\text{-}67$$

therefore

$$A_e + A_{es} = \frac{1 - N\bar{T}_s}{N\bar{T}_s} \quad K_{rc} \qquad 5\text{-}68$$

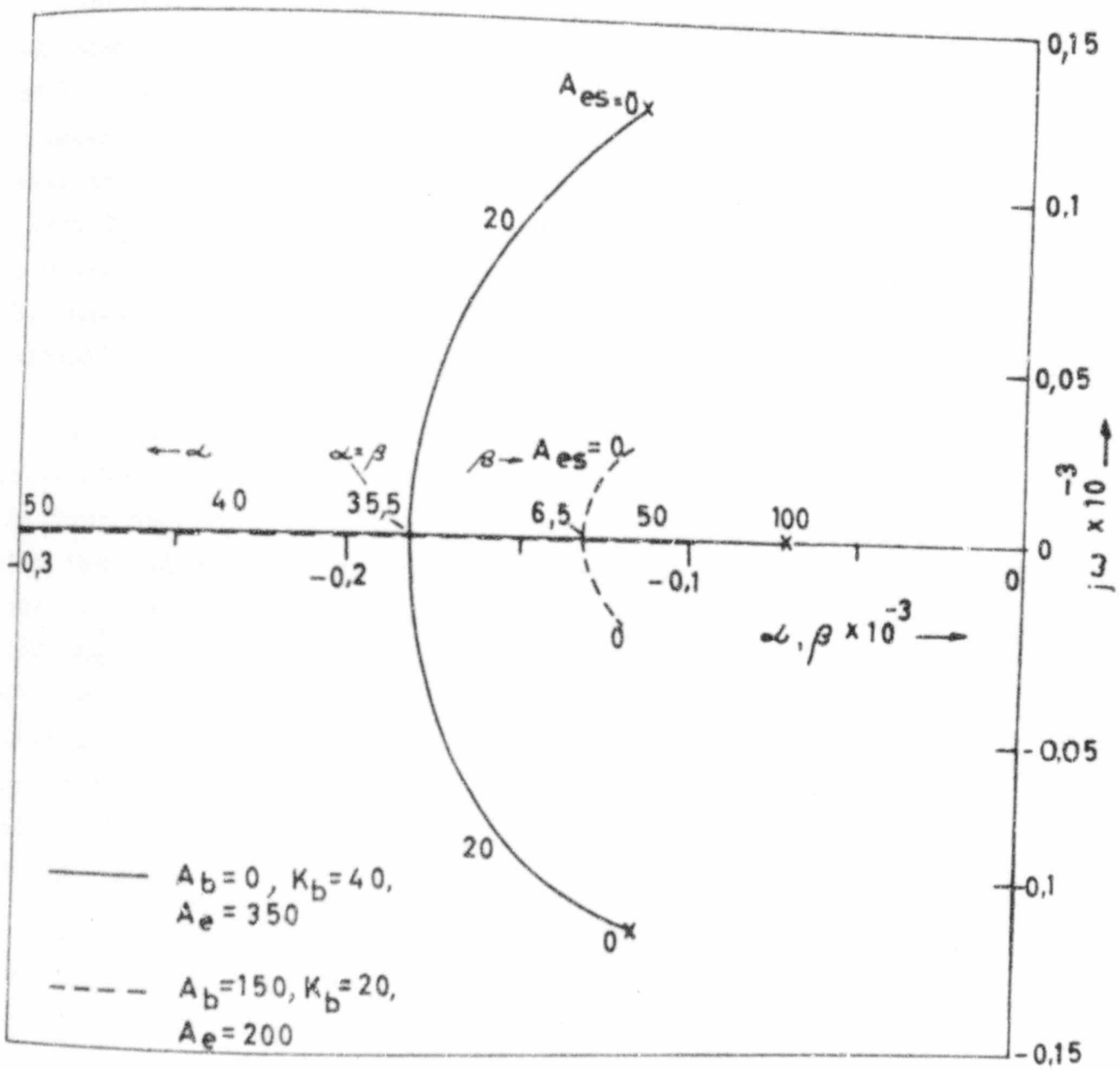


FIGURE 5.11

The locus of the roots of the closed loop equation 5-59 are plotted for values of A_{es} varying from 0 to 100. The solid and broken lines represent the locus when the ambient air temperature is in the region of 35°C and 32°C respectively. The position of the roots α and β are indicated by equivalent values of A_{es}. The values of A_{es} on the real axis apply to the solid line.

The equation 5-68 is identical to equation 5-55, therefore the value of A_e determined in the previous section is actually the sum of A_e and A_{es} for $T_a > 34°C$.

The rate of evaporative heat loss required to maintain thermal equilibrium in an environment with $T_a = 28°C$ and $V = 0,67$ m/s is less than 3 W. It is therefore safe to assume that the steady state values of A_e and A_{es} are small in this environment. Knowing the values of $A_e + A_{es}$, T_c and T_s for $T_a > 34°C$ and for $T_a = 28°C$, it is possible to estimate the value of $A_e + A_{es}$ in the region $28°C > T_a > 34°C$. The value is probably similar to the value of A_e which was calculated in the previous section.

In order to isolate the value of A_e or A_{es} from equation 5-68, one must examine the transient response. The damping factor and the peak value of T_s is dependent upon the value of A_e and A_{es}. The peak value of T_s and the time, t_p, at which it occurs after a change in air temperature may be obtained from the experimental results. If various sets of values of A_e and A_{es}, which satisfy equation 5-68, and the value of t_p are substituted into the numerical solution for T_s, equation 5-24, then the set which gives the desired peak value of T_s identifies both A_e and A_{es}.

A computer model simulation provides a convenient and more accurate method of evaluating A_e and A_{es} as the model is not confined to a small disturbance which is the requirement of the linear analysis. Two non-linear control functions representing the relation between A_e and T_c, and A_{es} and T_s are estimated. Each function, or curve, is made up from a set of five straight lines; the slope of the line represents either A_e or A_{es} and the sum $A_e + A_{es}$ is given by equation 5-68.

The response of the model is examined and the control functions altered until both the transient and the steady state temperatures agree. The model was tested first with the initial air temperature equal to 35°C and then the

initial air temperature was decreased to 28°C. It was necessary to include peripheral blood flow control in these tests. The characteristics derived in the first section (Figure 5.8) were used with the assumption that $A_{bs} = 0$.

The response of the model, using the most suitable set of control characteristics, is illustrated in Figure 5.12. Sweat control is initiated from both core and skin temperature. If this record is compared with the superimposed experimental results and with the previous computer simulation in Figure 5.10, the improvement caused by the term A_{es} is obvious. The transient skin temperature peaks are much smaller, the settling [illegible] of T_c has increased, the transient shape of T_c and t[illegible]porative heat loss are more accurate and the secc[illegible]noot in the skin temperature transient has dissapeared.

The evaporative control characteristics are illustrated in the top drawing of Figure 5.13. The value of A_e and A_{es} were determined for each of the four transient records shown in Figure 5.1. The value of the coefficients increases with temperature, the value of A_e is approximately ten times greater than the value of A_{es}.

This study has examined the influence of the term A_{es} on the responce of the controlled system; the skin temperature component of peripheral blood flow control action A_{bs}, was excluded. The condition in which the peripheral blood flow control is initiated by both T_c and T_s is examined now.

The term A_{bs} has a negative sign in the numerator of equation 5-59 and 5-65. If $R_b A_{bs} = 1$, then $\overline{T}_c = 0$; this means that there will be no change in T_c when T_a causes a disturbance. However, if $R_b A_{bs} > 1$, then the steady state increment, $\overline{T}_c$, will have a polarity which is opposite to that of the increment $\overline{T}_a$. A rise in air temperature will cause a fall in core temperature. This does not occur with man. Experimental results indicate that $\overline{T}_c$ has a finite value and has the same polarity as $\overline{T}_a$, so that the value of the term $R_b A_{bs} < 1$. If $R_b A_{bs} > 1$ the response of the model would be unstable and drift into a condition of saturation.

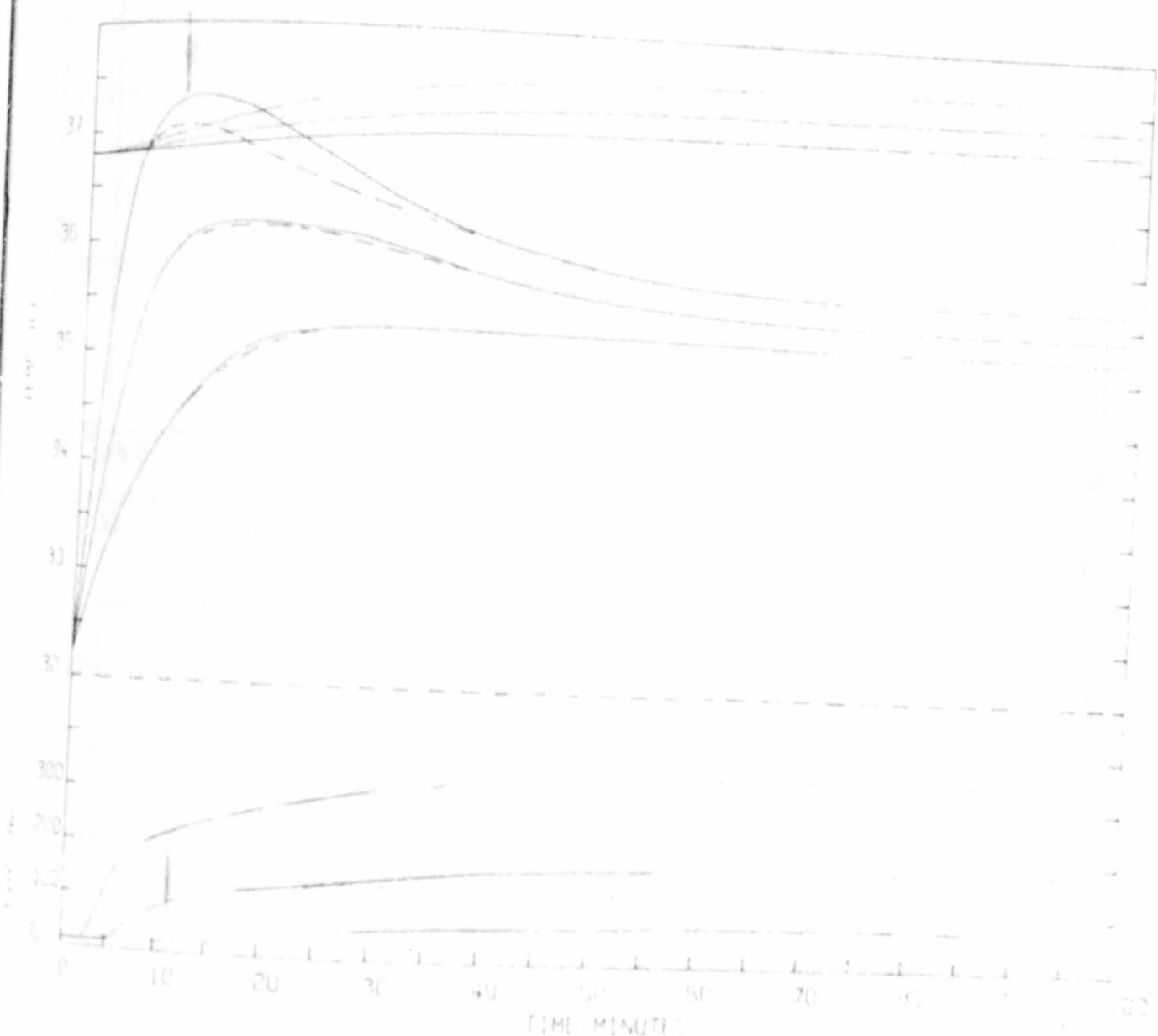


FIGURE 5.12

A computer plot of the models response to a step change in air temperature from 28 °C to 35 °C, 40,5 °C and 49 °C, V = 0,67 m/s. Control is initiated from the core and skin temperature.

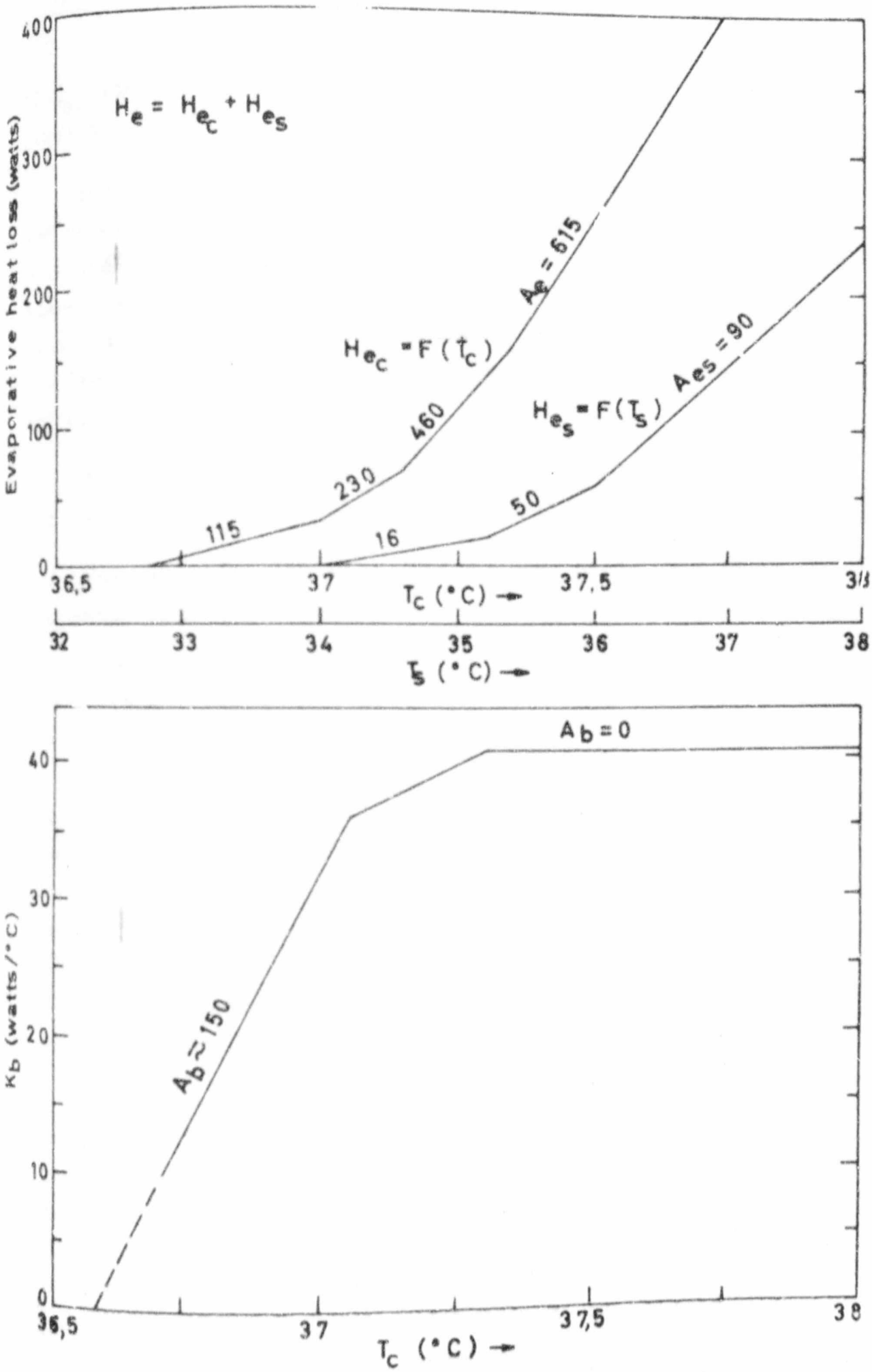


FIGURE 5.13

The evaporative and peripheral blood flow control characteristics.

If A_{bs} does exist, it must have a small value, namely < 25 since $R_b \approx 0,04$.

The term A_{bs} appears in the numerator of equation 5-63 and 5-64. This term decreases the influence of A_{es} and it will therefore increase the peak value of the skin temperature transient. The peripheral blood flow does, however, attain a maximum value rather rapidly and it will influence the transient response of the body to changes only at ambient temperatures below 34°C.

The values of A_b and A_{bs} may be determined in a manner similar to that described for identifying A_e and A_{es}.

The relation between A_b and A_{bs} may be derived from the ratio between the equations 5-65 and 5-66, namely,

$$\frac{\bar{T}_c}{\bar{T}_s} = \frac{1 - R_b A_{bs}}{1 + R_b A_b} \qquad 5\text{-}69$$

This equation represents the ratio between the slope of the steady-state core and skin temperature curves given in Figure 4.15, page 126. Consider a change in air temperature from 28°C to 32,5°C. The values of $\bar{T}_c$ and $\bar{T}_s$ are given in Table5.2. By assuming values for A_b it is possible to calculate corresponding values for A_{bs}. A few examples are listed in Table 5.4.

Since the increase in skin temperature is ten times greater than that of the core temperature, the value of A_{bs}, for $A_b = 0$, is one tenth of that for A_b, when $A_{bs} = 0$. Any set of values for A_b and A_{bs}, within the range of values given in Table 5.4 will satisfy the steady-state experimental results, but they will, alter the transient temperature response significantly. The correct set of values may therefore be determined by substituting various sets of values of A_b and A_{bs} into the model and then comparing the

TABLE 5.4

Sets of values of A_b and A_{bs} which satisfy equation 5-69.

$\overline{NT}_s = 0,55$, $\overline{NT}_c = 0,055$, $K_b = 23,25$, $R_b = 0,043$

A_b	A_{bs}
209	0
200	0,93
150	5,9
100	10,9
50	16
0	20,9

transient response of the model with the experimental results. The transient response to a small change in ambient temperature, where maximum vasodilation does not occur, should be examined.

Figure 5.14 illustrates the response of the model to a step change in air temperature from 28°C to 32,5°C, with air velocity = 0,67 m/s. The four records represent four sets of values for A_b and A_{bs}. Note that as the value of A_{bs} increases, so does the skin temperature transient rise-time increase. The skin temperature transient has a distinct 'overshoot' which lasts for the duration of the record. The term A_{bs} does, in fact, cause a slow damped oscillatory response. No 'overshoot' was noticed in the skin temperature transient determined experimentally. By comparing the response of the model with the superimposed broken line, which represents the experimental results, it is clear that the value of A_{bs} is small and that it may therefore be neglected in these conditions which represent a resting man in a warm environment. A small value of A_{bs} will have even less influence on the transient temperature response of the body when the body is exposed to a higher ambient temperature

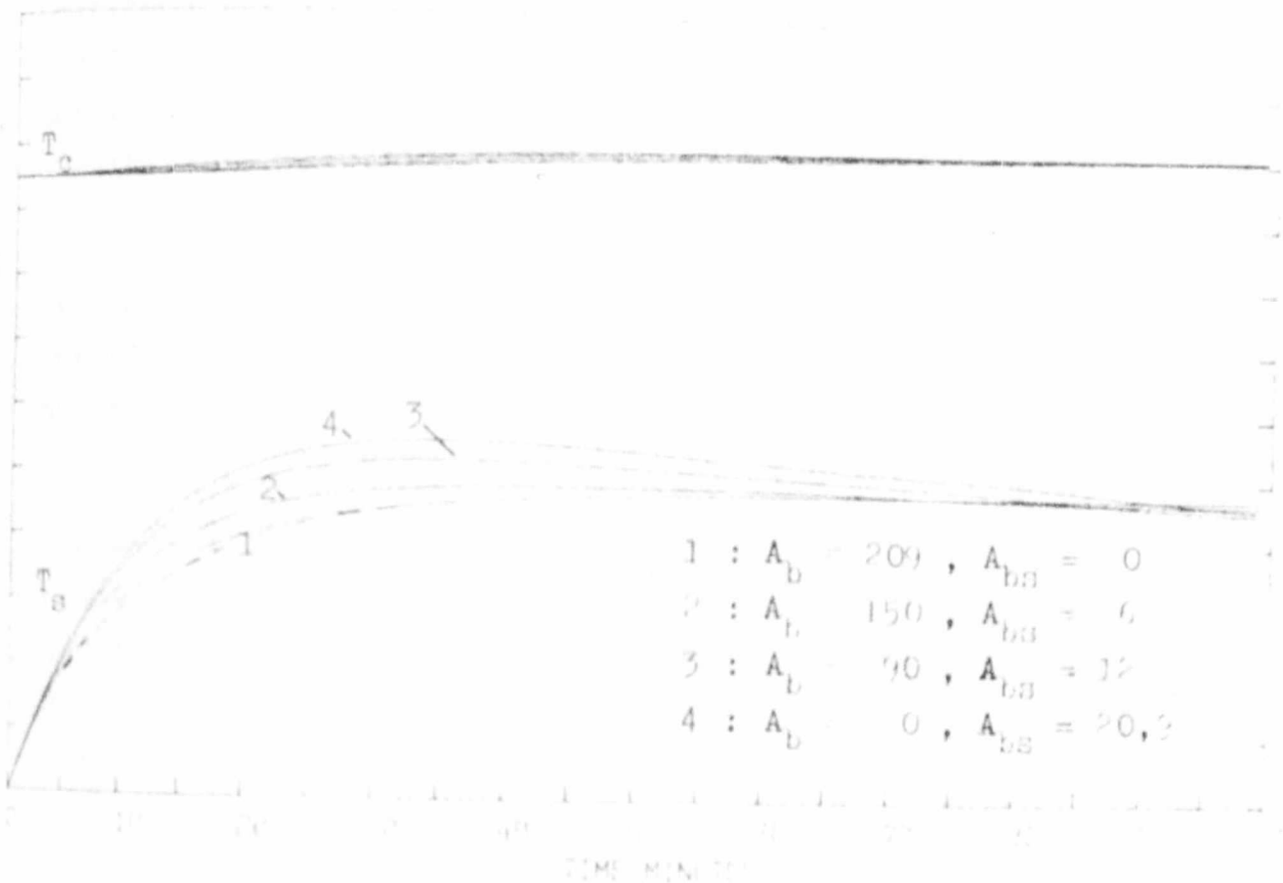


FIGURE 5.14

A computer plot of the models response to a step change in air temperature from 28°C to 32,5°C, V = 0,67 m/s. The four records represent four sets of values of A_b and A_{bs} which satisfy equation 5-69. The runs are used to determine the value of A_b and A_{bs}.

because maximum vasodilation occurs very rapidly after exposure to heat.

The term A_{bs} might be significant in a situation in which the body is exposed to cold. This analysis has confirmed the results obtained recently by Brengelman et al. (1973) who reported that they could not find any correlation between vasomotor tone and skin temperature as a source of control in a warm environment.

The control characteristics illustrated in Figure 5.13 are therefore valid for the full range of ambient air temperatures between 28°C and 49°C. They apply to a resting man exposed to an increase in ambient temperature.

Both Nadel (1971) and Mitchell (1972) have found that the skin temperature has a local modulation effect on sweating. This means that the neuro-motor control is temperature sensitive. Nadel suggests a small non-linear multiplication term which is effective only when the skin temperature is above 35°C, namely

$$H_e = 197(T_c - 36,7) + 23(T_s - 34)\, e^{0,1(T_{ws} - 34)} \qquad 5\text{-}70$$

where T_{ws} is the weighted skin temperature.

This multiplication term will certainly reduce the skin temperature transient peak yet have very little effect on the steady state temperatures.

The response of the model with an evaporative control action given by Figure 5.13 and with multiplication term

$$H_e = H_e \times e^{0,2(T_s - 35,5)} \qquad 5\text{-}71$$

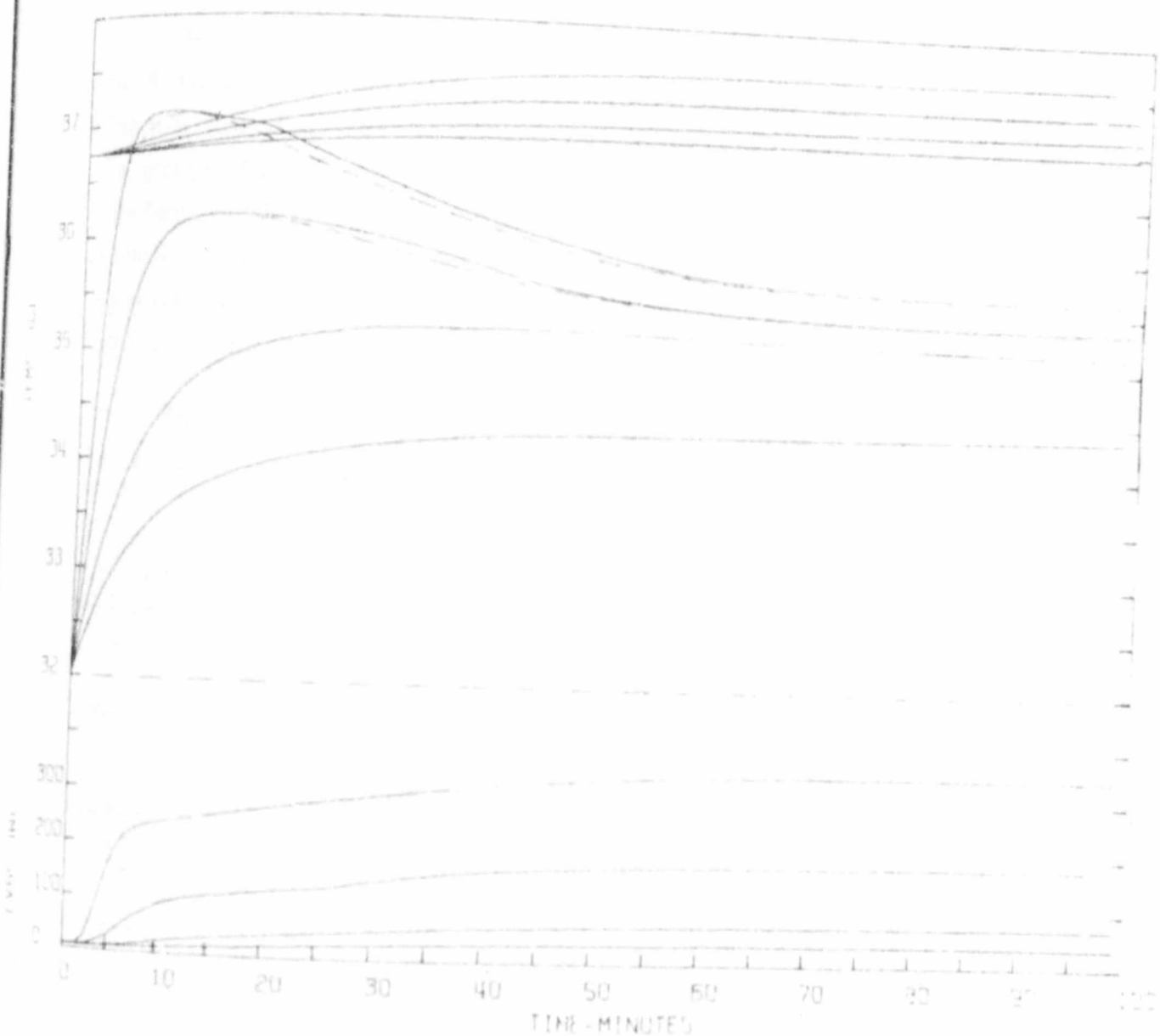


FIGURE 5.15

A computer plot of the response of the model to step changes in air temperature from 28°C to 32,5°C, 35°C, 40,5°C and 49°C, the air velocity = 0,67 m/s. Control is initiated from the core and skin temperatures, the latter having an additive and a multiplication term.

is illustrated in Figure 5.15. The multiplication term is similar to that suggested by Nadel

5.1.3 Proportional and rate control

Because thermo-detectors have been shown to be sensitive to a rate of change of skin temperature it has been suggested that a control action could be initiated by a source which is proportional to the rate of change of skin temperature, (Refer to Chapter 2). Nadel et al. (1971) and Banerjee et al. (1974) noticed that the decrease in the rate of sweating is dependent upon the rate of change of skin temperature. The subject has never been examined analytically.

The closed loop equations (5-8 and 5-9) may be written as follows

$$\frac{T_c(s)}{T_a(s)} = \frac{(1 - R_b A_{bs} - sR_b A_{bd})/(R_b R_{rc} C_c C_s (1+\frac{1}{C_s}(A_{ed}-A_{bd})))}{s^2 + sQ + R} \quad 5\text{-}72$$

and

$$\frac{T_s(s)}{T_a(s)} = \frac{(1 + R_b A_b + R_b C_c s)/(R_b R_{rc} C_c C_s (1+\frac{1}{C_s}(A_{ed} - A_{bd})))}{s^2 + sQ + R} \quad 5\text{-}73$$

where

$$Q = \frac{(R_b+R_{rc}+R_b R_{rc}(A_{es}-A_{bs}))C_c + (R_{rc}+A_b R_b R_{rc})C_s + A_{ed}R_{rc} + \text{contd. } R_b R_{rc}(A_b A_{ed} - A_e A_{bd})}{R_b R_{rc} C_c C_s (1 + (A_{ed} - A_{bd})/C_s)} \quad 5\text{-}74$$

and

$$R = \frac{1 + R_b A_b + R_{rc}(A_e + A_{es}) + R_b R_{rc}(A_b A_{es} - A_e A_{bs})}{R_b R_{rc} C_c C_s (1 + (A_{ed} - A_{bd})/C_s)} \quad 5\text{-}75$$

Maximum rate of change of skin temperature occurs immediately after a change in air temperature. The rate control action will therefore only influence the transient response within the first few minutes after a disturbance.

The term A_{bd} and A_{ed} have little effect on the values of Q and R (equations 5-74 and 5-75) and do not alter the time constants significantly.

The initial slope of the skin temperature transient is given by

$$\frac{dT_s}{dt} = \frac{1}{R_{rc}C_s(1 + R_b R_{rc}(A_{ed} - A_{bd}))} \quad \text{(for } t = 0_+\text{)} \qquad 5\text{-}76$$

(refer to Appendix A4)

The term A_{ed} will cause the value of equation 5-74 to decrease slightly while A_{bd} will cause it to increase slightly.

If the sweat control action is sensitive to positive rate of change of skin temperature, sweating will commence rapidly after a step increase in air temperature.

Unfortunately, because of experimental delays mentioned in Chapter 4, it was not possible to commence recording from the instant at which the subject was moved to the new environment. All the experimental results show that the insensible heat loss commences soon after a step change in temperature. Part of this heat loss is due to the insensible respiration heat loss from the subject, the value of this loss being constant for the duration of the experiment.

Although it is difficult to evaluate the rate control action, because of experimental limitation, it is useful to examine the response of the model with a rate control action. Figure 5.16 illustrates the response of the model to a step change in air temperature from 28°C to 46°C. The two records illustrate a sweat control action with and without a rate control component (A_{ed} = 500 and A_{ed} = 0 respectively). The record should be compared with the superimposed broken line which represents the experimental results taken from Figure 4.9. The rate control component although large in value, causes little change to the transient temperature

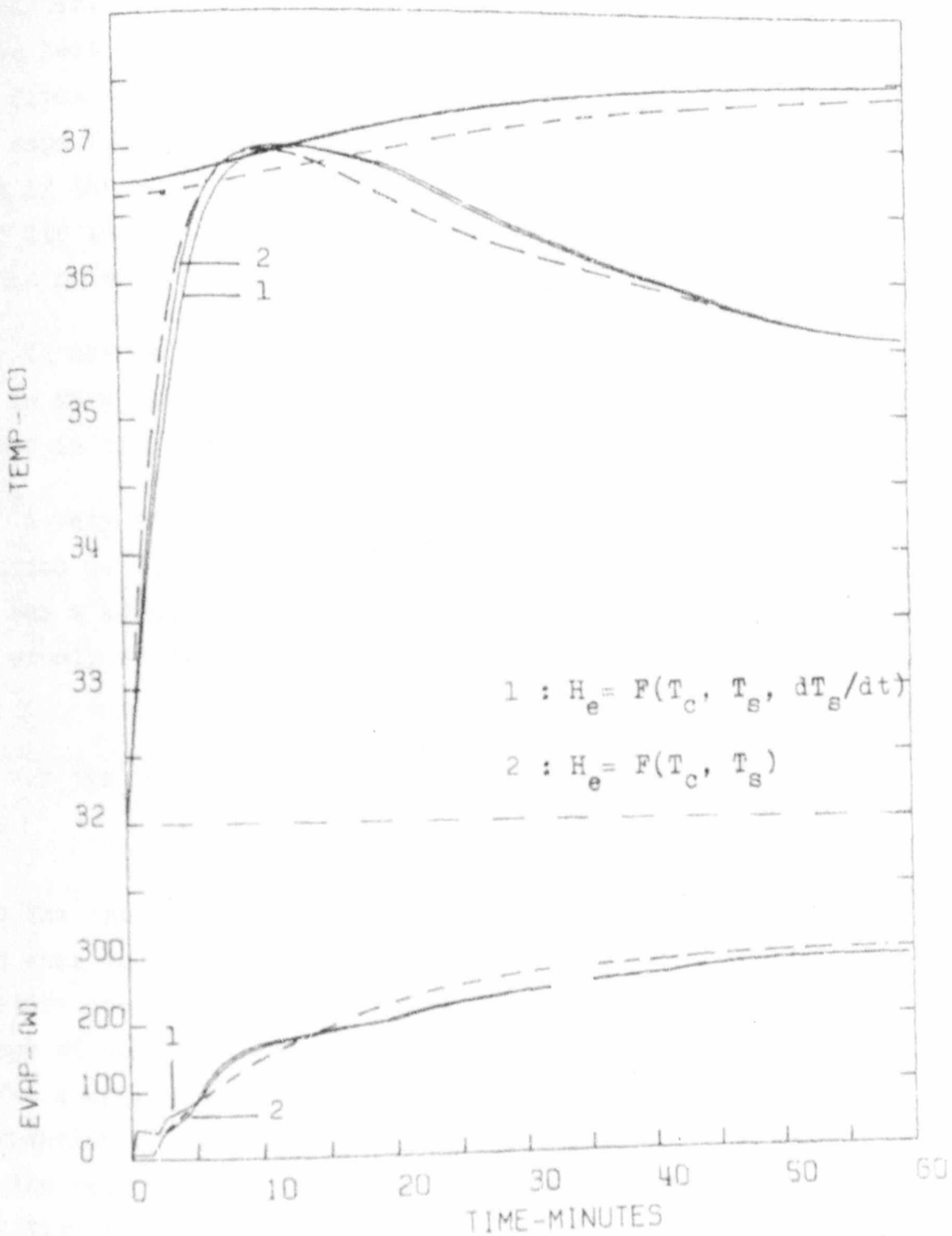


FIGURE 5.16

A computer plot of the models response to a step change in air temperature from 28°C to 46°C, V = 0,67m/s. The two records show the difference between the response of the model with, and without a sweating rate control action. The superimposed broken lines are the experimental results taken from Figure 4.9.

characteristics as predicted. The small additional evaporative heat loss due to the rate component which occurs within the first three minutes of starting the record, is evident. The experimental evaporative results for $0 < t < 5$ suggest that if there is a rate control component, it is unlikely that its value will exceed the value of A_{ed} demonstrated by the model.

It may be concluded, therefore, that unless the value of A_{es} is very large, the rate control action will cause little change in the transient characteristics of either T_c or T_s.

A very significant term occurs in the numerator of equation 5-72, namely, $-sR_bA_{bd}$. This term is time-dependent and has a negative sign. It was shown in Section 5.4.2 that the steady state term

$$-R_bA_{bs} < 1$$

If the rate control component A_{bd} is large enough to make

$$sR_bA_{bd} > 1$$

then the transient component $\Delta T_c(s)$ will have a negative sign when there is a rapid change in skin temperature. The negative component will dissapear as soon as the rate of change of skin temperature decreases and $sR_bA_{bd} < 1$. The Series 4 experiments were designed specifically for the observation of the rectal and the oesophageal temperatures. All the records show that the oesophageal temperature has a significant negative slope during the first five minutes after a step change in air temperature. With the exception of the experiments in which the subject was exposed to a very high ambient temperature, the rectal temperature had an initial negative slope (refer to Figure 4.9 and Figures A21toA25 in Appendix A2). Clearly, peripheral blood flow is dependent upon the rate of change of skin temperature. There is no other factor in the transient expression which

can cause an initial decrease in core temperature following an increase in air temperature. A very rapid increase in peripheral blood flow causes heat to be transferred rapidly to the surface, thus resulting in a temporary fall in core temperature. It was shown that if the peripheral blood flow was proportional to skin temperature, a 'negative change' in core temperature could arise but that the change will be permanent and that an unnatural unstable condition will occur.

The fact that the oesophageal temperature, which is an indication of arterial temperature, decreases substantially, confirms the fact that the mean blood temperature has decreased. The arterial temperature will decrease more than the core temperature as the circulating system has far less thermal inertia.

Figure 5.17 illustrates the response of the model to a step change in air temperature from 28°C to 40,5°C. The peripheral blood flow control action is proportional to core temperature and the rate of change of skin temperature. The record shows the small decrease in core temperature, due to the rate control action, within the first three minutes of changing the environmental temperature. There is no significant change in the transient skin temperature.

The response of the model confirms the analysis that the peripheral blood flow control action is initiated by a signal which is proportional to the rate of change of skin temperature. The rate control action has little influence on the temperature response of the body when exposed to a heat stress.

5.5 Summary

This study has shown that a simple model can be used to examine the behavioural temperature control characteristics and it can simulate the temperature response of a resting

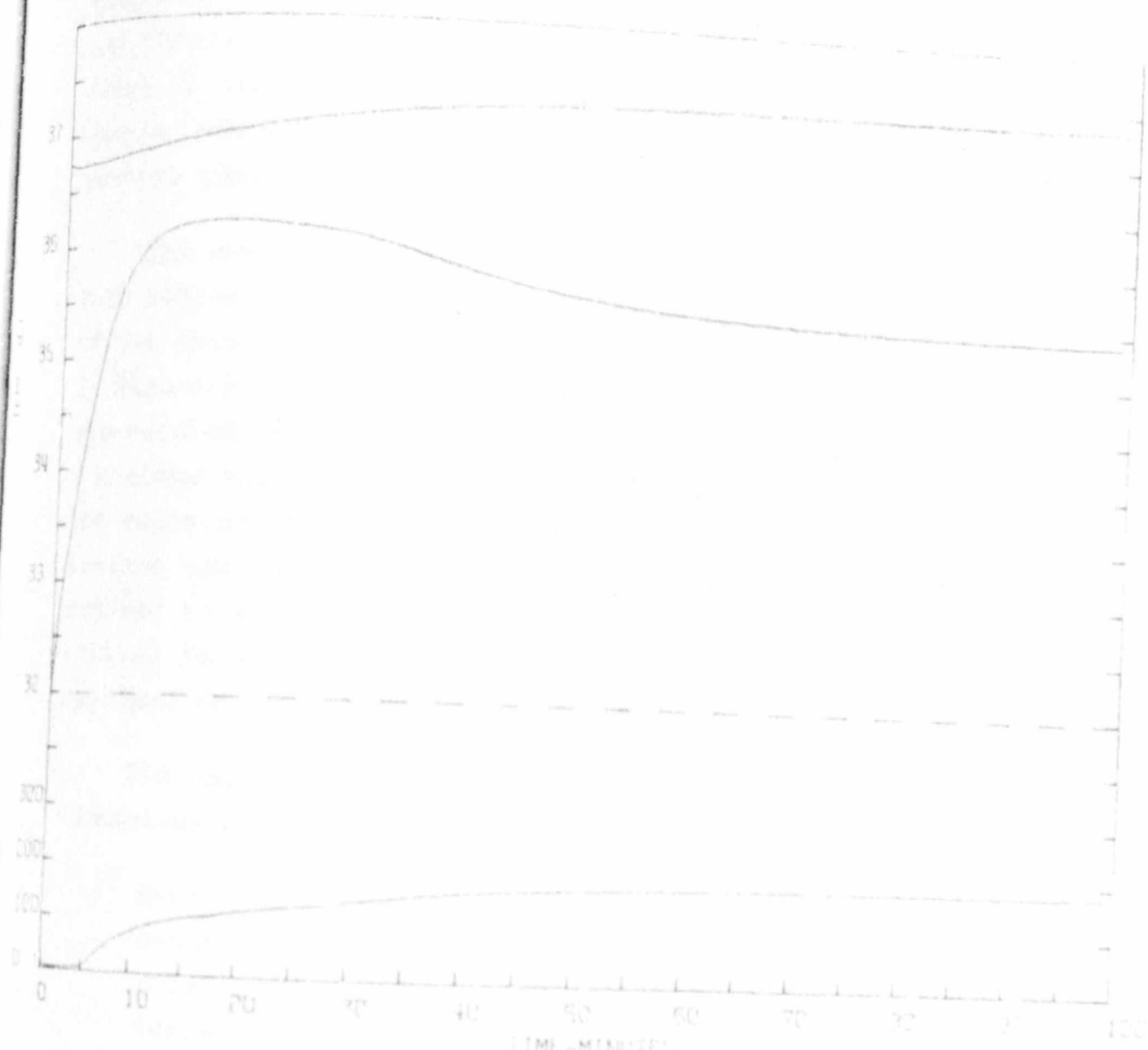


FIGURE 5.17

A computer plot of the models response to a step change in air temperature from 28°C to 40,5°C, $\dot{V}$ = 0,67 m/s. The peripheral blood flow control action is initiated by a signal which is proportional to the core temperature and the rate of change of skin temperature. Note the small decrease in core temperature caused by the rate control term within the first three minutes of the record.

man subjected to an increase in air temperature. The control characteristics have been identified from both the transient and steady state data and therefore apply to the full dynamic range of temperature. The test in the first section of this chapter showed that it is not possible to determine the true control characteristics from steady state data alone.

The evaporative control characteristic is non-linear, both components are similar in shape to the lower portion of the warm neuro-sensor characteristics described in Chapter 2, Figure 2.2 . The peripheral blood flow control action, represented by the change in physiological conductance, has a maximum value when the rectal temperature exceeds 37.15°C. The value of physiological conductance decreases with temperature and is likely to continue to decrease when man is exposed to a cold stress. The temperature characteristic is similar to that illustrated in Figure 2.4 which shows the combined response of warm and cold neuro-sensors.

The important thermoregulatory characteristics are summarised as follows:

1) Evaporative heat loss is responsible mainly for the control of core temperature in a warm environment. This control action can reduce the disturbance in core temperature, caused by a change in environment temperature, by a factor of 1/20.

2) The sweat control action is initiated by both the core and skin temperatures. The sensitivity of the core temperature component is approximately ten times greater than the sensitivity of the skin temperature component. The sensitivity of the control action depends upon the magnitude of the heat stress. The control characteristics which have been identified are very non-linear, they may be represented by a linear expression only over a limited range of temperatures. The control sensitivity increases with temperature until some upper limit is reached. This limit is determined either by the peak thermo-sensor activity or by some other physiological factor.

Author Atkins Arthur Reginald
Name of thesis A Study Of Temperature Control In The Human Body By Experiment And Computer Simulation. 1975

PUBLISHER:
University of the Witwatersrand, Johannesburg
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