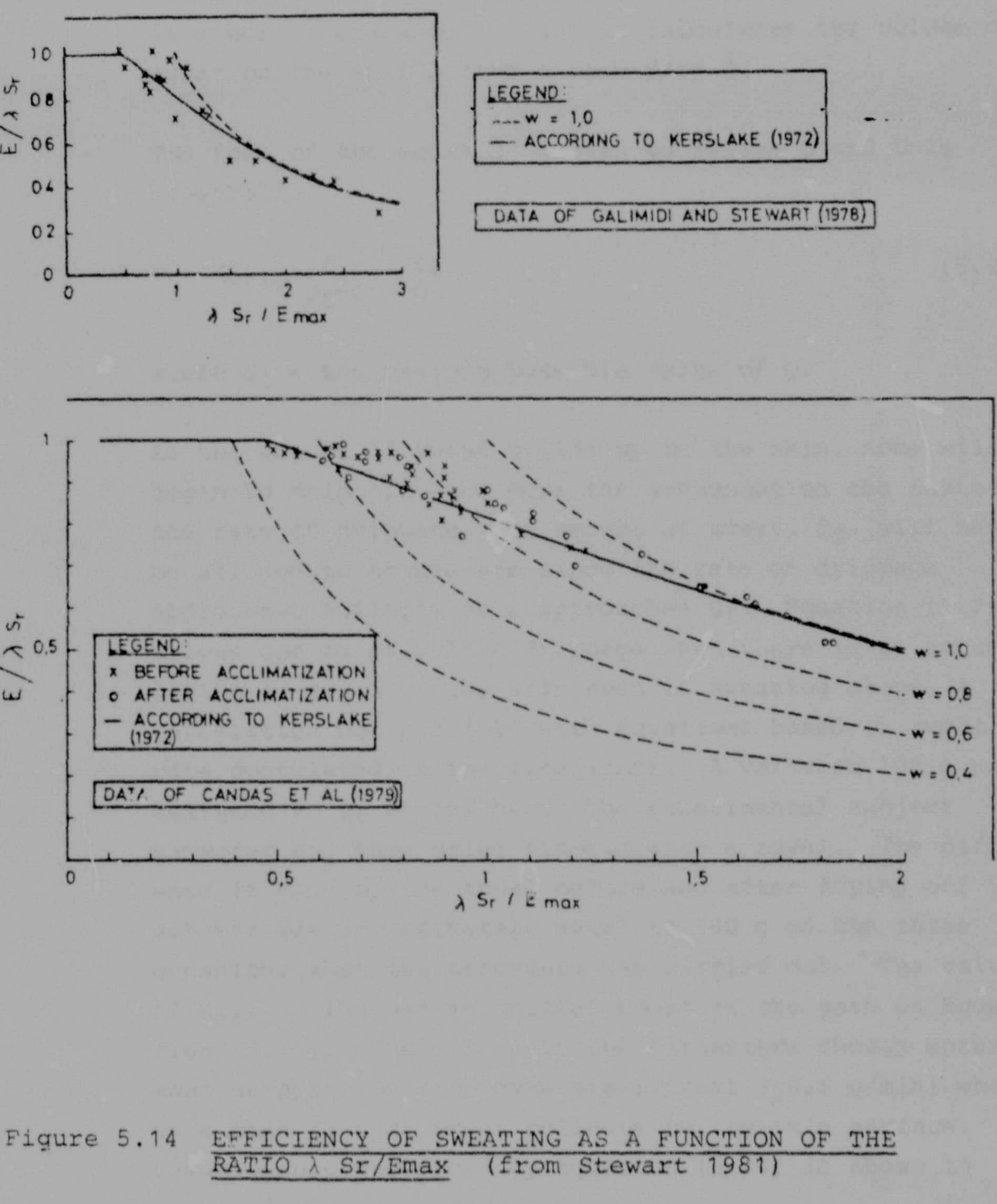

Figure 5.14 EFFICIENCY OF SWEATING AS A FUNCTION OF THE RATIO λ Sr/Emax (from Stewart 1981)

The block diagram, Figure 5.13, indicates that the amount of dripped sweat is to be calculated from the quantity of sweat accumulated on the skin. The block between $\dot{Q}$ and Q is a pure ingegrator in that it calculates the volume of sweat on the skin Q from a flow rate $\dot{Q}$.

The form of the equation chosen to relate Q and D is hyperbolic.

$$D = K_{drip}\left(\frac{1}{Q_f - Q} - \frac{1}{Q_f}\right) \qquad (5.24)$$

where Q_f = the maximum possible value of Q.

As the amount of sweat builds up on the skin, some will begin to drip off, the more the accumulation the faster the rate of drippage. An amount of sweat, Q_f, will never be allowed to accumulate since the rate of drippage approaches infinity as Q approaches Q_f. Equation (5.24) allows one to calculate drippage when there is an accumulation of sweat on the skin even if sweating stops, a calculation not possible with equations based on sweat rate postulated in the literature. A value of 100 g was assigned to Q_f as follows. The experimental subject showered and then dried himself with a towel. The difference in mass of the towel before and after drying off the subject was approximately equal to 100 g on the three occasions that the procedure was carried out. The value of K_{drip} = 100 was an initial guess at the gain on Equation (5.24). The values of the parameters chosen ensure that drippage only becomes significant ($\pm$0,5 g/min) when more than 33 g of sweat collects on the skin surface. The relationship described by Equation (5.24) is shown in Figure 5.15.

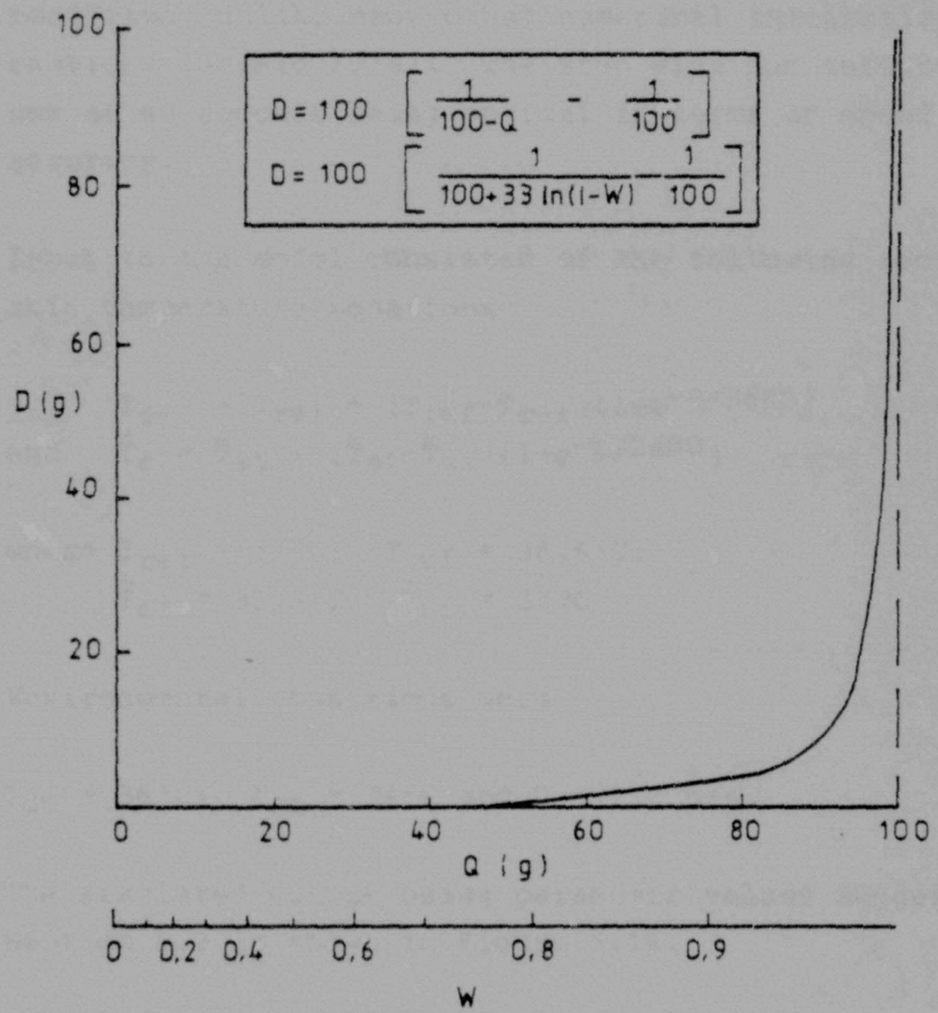

Figure 5.15 DRIPPAGE PLOTTED AGAINST Q AND W

5.3 Model Simulation and Parameter Optimization

In order to test the response of the model to given rectal and skin temperature inputs, a continuous systems simulation routine was written in BASIC language on the Hewlett Packard 9845A desktop computer. The basis of the routine was a Fourth Order Runge-Kutta integration, an advantage of this method being that it can begin from any initial condition, unlike many other numerical integration routines (Gerald 1978). The step size for integration was set at 60 seconds being optimal in terms of speed and accuracy.

Input to the model consisted of the following rectal and skin temperature equations

$$T_{re} = T_{rei} + (T_{ref} - T_{rei})(1 - e^{-t/3600}) \qquad (5.25)$$

and

$$\bar{T}_s = \bar{T}_{si} + (\bar{T}_{sf} - \bar{T}_{si})(1 - e^{-t/2400}) \qquad (5.26)$$

where $T_{rei} = 37°C$; $T_{ref} = 38,6°C$;
$\bar{T}_{si} = 35,5°C$; $\bar{T}_{sf} = 37°C$

Environmental conditions were

$T_{db} = 36°C$; $T_{wb} = 34°C$ and $V = 1,2$ m/s.

The simulated output using parameter values suggested in Section 5.2 is shown in Figure 5.16.

Agreement between the model and actual experimental data was tested using three different experimental days. In order to use the experimental results in the simulation and parameter optimization routines, certain preparation of the data was necessary.

The Runge-Kutta routine evaluates the integrand at half the time step interval. In order to interpolate rectal and skin temperatures at thirty second intervals from

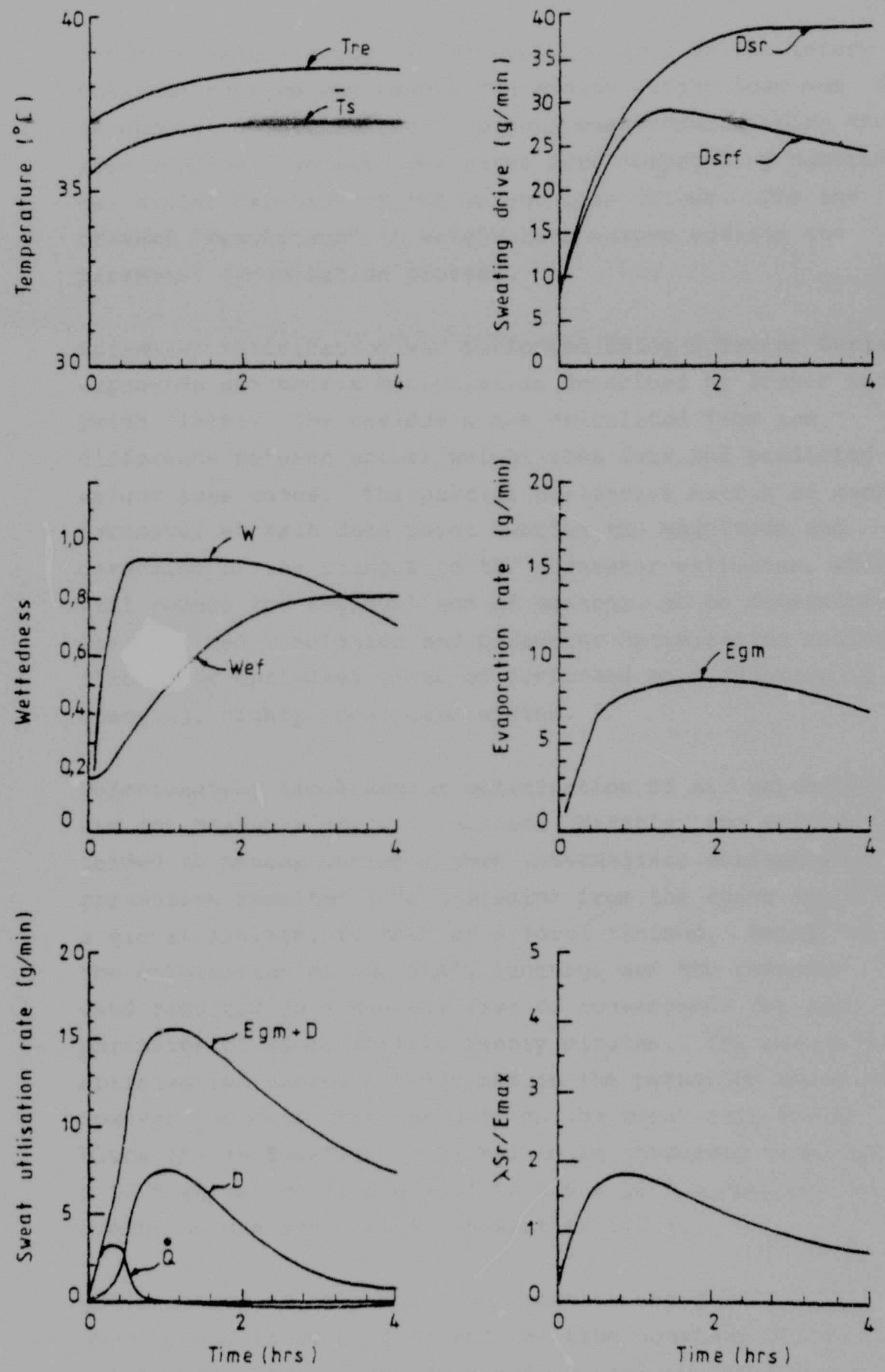

Figure 5.16 SIMULATED SWEAT RATE MODEL

discrete values every two minutes, a Cubic Spline interpolation routine was used. Ten minute weight loss was interpolated between twenty minute measurements using the same routine. Weight loss rates were computed by numerical differentiation of the weight loss values. The increased "resolution" in weight loss values assists the parameter optimization process.

Parameter optimization was performed using a Taylor Series expansion and matrix manipulation described by Draper and Smith (1966). The residuals are calculated from the difference between actual weight loss data and predicted weight loss rates. The partial derivative matrix of each parameter at each data point enables the magnitude and direction of the changes to the parameter estimates, which will reduce the residual sum of squares, to be determined. The combined simulation and parameter optimization routine allows for optimization to be performed on a dynamically changing, highly non-linear system.

Unfortunately simultaneous optimization of all parameters was not possible for two reasons. Firstly, the simulation tended to become unstable when intermediate estimates of parameters resulted in a deviation from the route towards a global minimum, to that of a local minimum. Secondly, the combination of the BASIC language and the computer used resulted in a minimum time of convergence for each parameter of approximately twenty minutes. The parameter optimization exercise described in the paragraph above did however indicate that the gain on the sweat rate drive block (h) in Equation (5.5) had to be increased from 1,47 $\times 10^{-4}$ kg/sec m^2 ($\pm$16 g/min) to 2,6 $\times 10^{-4}$ kg/sec m^2 (28 g/min) as was anticipated in Section 5.2.1.

Optimization of only the time constant and gain of the sweat gland fatigue block and the time constant of the wettedness effect block resulted in good agreement between measured and predicted response on the three experimental days chosen. Results of the optimization exercise are shown in Figures 5.17, 5.18 and 5.19. Table 5.1 lists the environmental conditions, work rates and parameter estimates for these three days. Unfortunately, the evaporation measurement on the second day was erroneous and was therefore omitted from the plot.

Table 5.1 VALUES OF PARAMETERS ESTIMATED FOR THREE SAMPLE DAYS

	Day 1	Day 2	Day 3
T_{db} (°C)	33	37	21
T_{wb} (°C)	31	35	19
V (m/s)	1,2	1,2	1,2
M (W/m^2)	254	54	236
Sweat Gland Fatigue Parameters			
$C_n(0,0)$	2,9x10^{-5}	3,6x10^{-5}	2,5x10^{-4}
$C_d(0,0)$	1,6x10^{-4}	1,5x10^{-4}	1,7x10^{-4}
τ (mins)	104,2	111,1	98,0
d.c. gain	0,18	0,24	1,5
Skin Wettedness Effect Parameters			
$C_n(2,0)=C_d(2,0)$	4,1x10^{-4}	1,2x10^{-4}	4,7x10^{-4}
τ (mins)	40,7	13,9	35,5

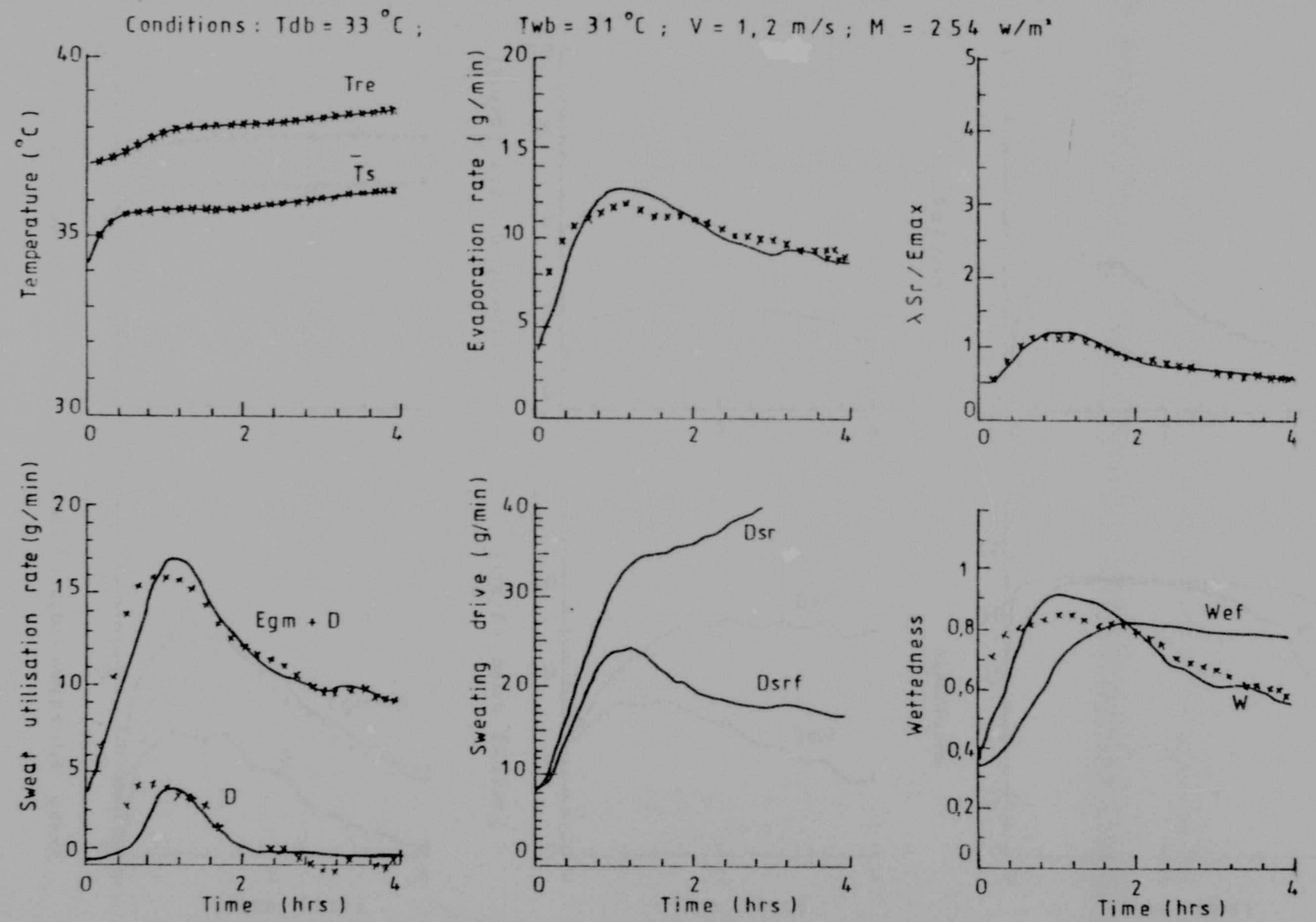

Figure 5.17 SIMULATED AND MEASURED RESPONSES FOR DAY 1

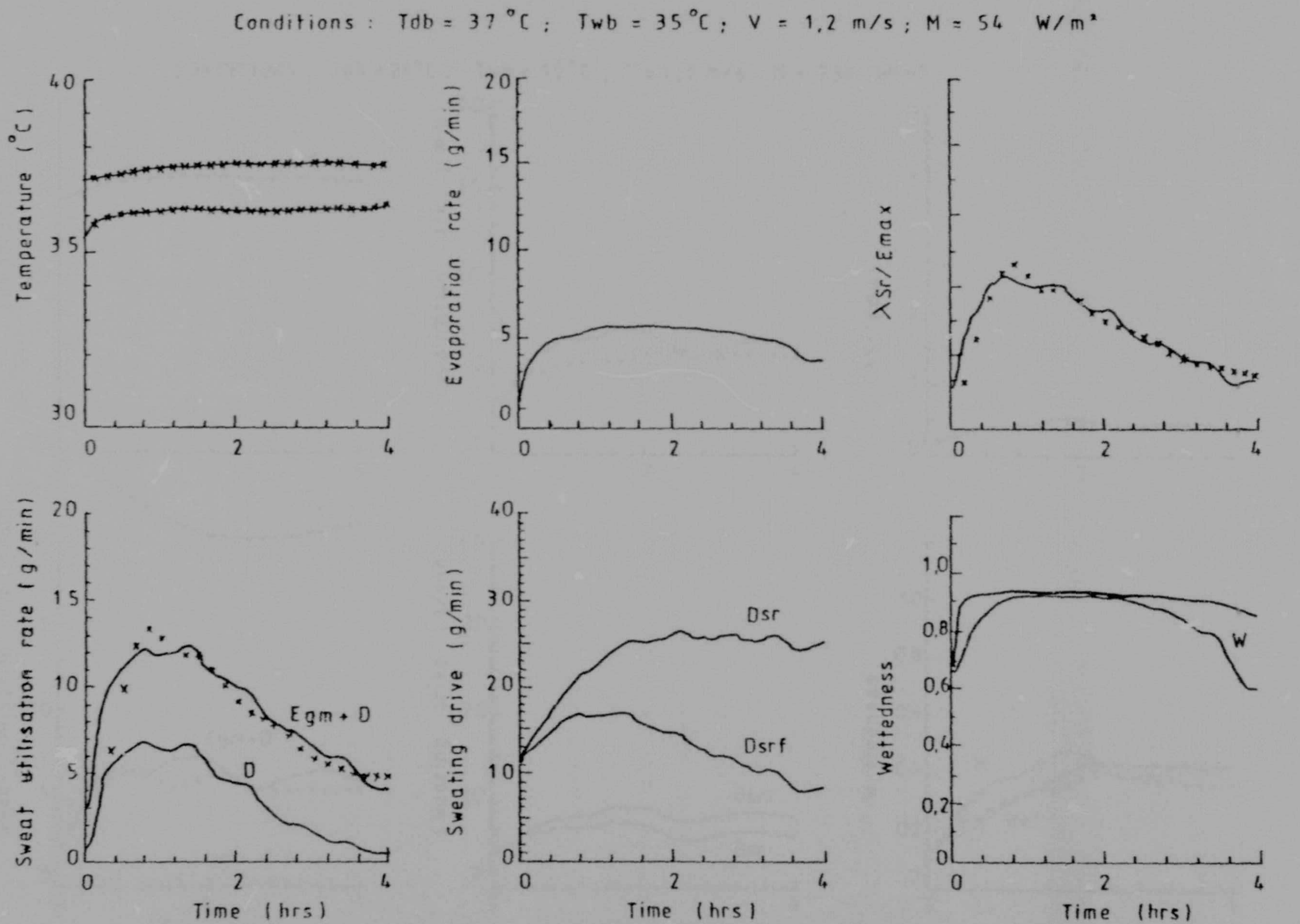

Figure 5.18 SIMULATED AND MEASURED RESPONSES FOR DAY 2

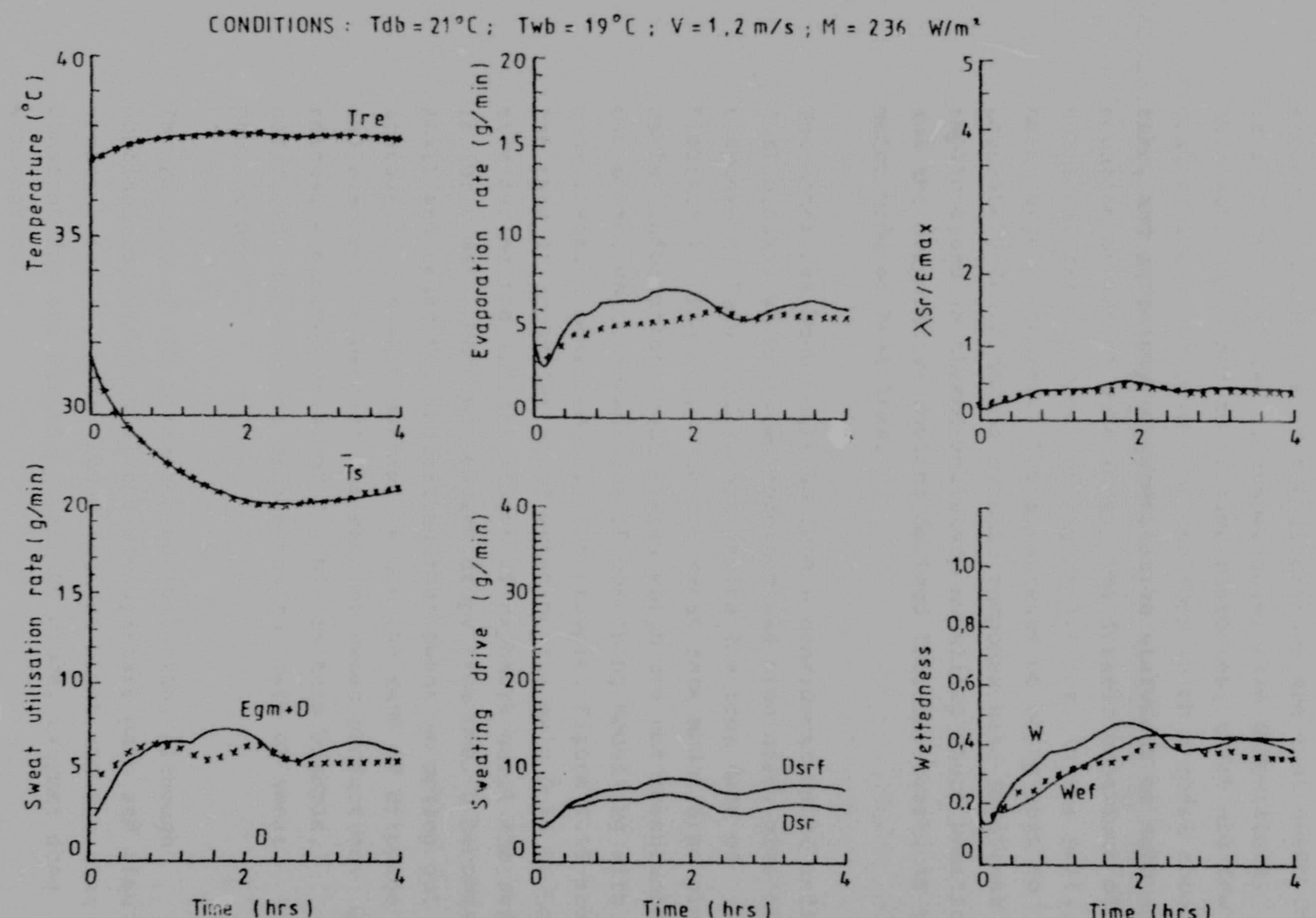

Figure 5.19 SIMULATED AND MEASURED RESPONSES FOR DAY 3

5.4 Discussion

Although indications in the literature are that sweat rate is a function of rectal temperature, skin temperature, skin wettedness and their time histories, there are few qualitative descriptions of the form which a model should take, and certainly no quantitative statement of such an equation or set of equations. The dynamic behaviour of the sweat rate response of Figure 5.1 has, in the past, been largely ignored. The advantages of being able to accurately describe the dynamic response have important implications in thermoregulatory modelling where sweating, and the evaporative cooling derived from the sweat, is the major mode of heat loss.

The model has been built up from a consideration of individual blocks, which, when combined and simulated, give the response of Figure 5.16, not unlike the true data of Figure 5.1. The output of the sweat rate model also gives useful information about states which are not measurable, one of the major advantages of combining modelling with non- invasive measurement. For example, Figure 5.16 shows the rate of accumulation of water on the skin $\dot{Q}$ to be positive during the initial stages of exposure until the skin is fully wet. Once wettedness drops from one, $\dot{Q}$ becomes small and negative, indicating that sweat is coming out of storage on the skin surface, since the rate of drippage and evaporation exceeds the rate of sweat production. $\dot{Q}$ reaches a maximum value of 3 g/min in this example, comprising 20 per cent of the maximum rate of sweat production.

The results of the parameter optimization, although confined to estimates of the steady-state gain and time constant for the sweat gland fatigue block and the time constant for the wettedness effect block, warrant some explanation.

Days 1 and 2 both consisted of step changes from a warm environment to hot environments. The three optimized parameters were of the same order for both days and agreement between data and prediction was good. The parameters did not differ by more than 20 per cent from those suggested in the derivation of the sweat gland fatigue and wettedness effect blocks. Both of these blocks play a significant role in the suppression of sweat production and neither can be omitted. Day 3 however, required a d.c. gain on the sweat gland fatigue block which was greater than unity. The resulting amplification of the sweat rate drive was acting to reduce the skin wettedness effect. The step change in conditions were from a warm environment to a cool environment. The skin temperature dropped substantially during exposure and the mean body temperature must therefore have been decreasing with a concomitant loss in body heat content. Atkins (1975) and Ringuest (1981) concluded that the controlling mechanisms are substantially different during body cooling, a factor which has not been included in the present model but will require further investigation.

The model which has been postulated provides a rational means of combining the individual effects which contribute to the control of thermoregulatory sweating. Sweat gland fatigue and skin wettedness have been introduced in such a way that their time histories are included in the overall response characteristic. Although some blocks in the model require experimental validation, the simulated responses are close to actual response data and as such the model forms the basis on which further studies may be planned.

CHAPTER 6

CONCLUSIONS

The important facts arising from the study may be summarized in terms of the two major sections of this dissertation, namely the literature review and the modelling exercises.

6.1 The Literature Review

The literature review was undertaken with the specific aims of firstly determining whether existing models could be used as a means of predicting the rectal temperature response of men exposed to heat stress, and secondly identifying specific areas of the model requiring investigation. The conclusions reached are:

1. Models of human thermoregulation can be broken down into two parts, the active or controlling system and the passive or controlled system.

2. Models of the passive system have advanced much further than those of the active system. Both steady-state and transient temperature profiles within the passive system can be calculated from a given set of boundary conditions.

3. The active system, particularly the heat loss mechanisms, have not been described in terms of all the physiological and physical variables which effect them.

4. Empirical equations have been used to describe instantaneous relationships between dynamic variables without considering the nature of the dynamic response.

5. Regression equations used to relate variables in the physiological conductance and sweat rate characteristics have been based on inadequate short-term "steady-state" data.

6. The way in which sweat rate decays with time during long exposures to the heat has never been mathematically stated only qualitatively described.

7. An equation relating physiological conductance to mean body temperature and metabolic rate has not been stated for acclimatized men. Such an equation has however been derived for unacclimatized men over a limited range of their response characteristic.

The review of the literature has led to the conclusion that existing thermoregulatory models cannot in their present form, be used as a means of predicting rectal temperature for the purpose of assessing heat stress and setting heat stress limits for typical South African mining conditions.

6.2 The Modelling Exercise

In order to accurately determine the physiological conductance response characteristic, detailed experimentation was carried out on a single nude acclimatized man. Analysis of the data revealed the following:

1. For the one experimental subject at least, physiological conductance can be expressed as a function of a mean body temperature driving signal and metabolic rate (see Equations (4.6a) and (4.6b)).

2. The expression derived for physiological conductance can be partially explained in terms of the distribution of blood flow and a simple two cylinder core and shell model of man.

3. The saturation level of physiological conductance at low weighted body temperature driving signal (≤36,2°C) is a linear function of the metabolic rate. The saturation level at high weighted body temperature driving signal (≥38,5°C) is an exponential function of the metabolic rate.

An innovative approach was adopted for the development of a model of thermoregulatory sweating. By combining qualitative descriptions in the literature with basic engineering control theory, a block diagram model of thermoregulatory sweating has been formulated. The main features of this model are listed below.

1. Sweat rate drive can be expressed in terms of a weighted body temperature driving signal and the local effect of skin temperature (see Equations (5.5a) and (5.5b)).

2. Sweat gland fatigue is a dynamic effect and can be expressed in terms of a phase lead network (see Equation (5.10)). The time constant of the decay is of the order of 120 minutes.

3. The extent of skin wettedness is dependent on the quantity of water accumulated on the skin surface (see Equation (5.14)).

4. The skin wettedness has a dynamic effect on the suppression of sweating (see Equation (5.17)). With increasing sweat suppression, the time constant of the decay is of the order of 80 minutes. With decreasing sweat suppression, as the skin dries off, the time constant of the decay is approximately ten times longer, mathematically accounting for the hystereis effect shown in Figure 5.11.

5. The quantity of sweat which drips off the body is dependent on the amount of sweat accumulating on the skin. Drippage has the effect of never allowing the skin wettedness to reach one (see Equation (5.24)).

The dynamic model of thermoregulatory sweating has been simulated, and can, with good accuracy, reproduce the form of the sweat rate response observed during the detailed conductance experimentation.

The way in which the physiological conductance and sweat rate models can be combined, with the controlled system, to synthesize a thermoregulatory model has also been suggested.

APPENDIX I

Table I.1 PHYSICAL CHARACTERISTICS OF THE EXPERIMENTAL SUBJECT

Age	26 years
Mass	60 kg
Height	1,635 m
Surface area (Hardy and Du Bois)	1,77 m^2
Surface area (Photodermoplanimeter)	1,81 m^2

APPENDIX II

Table II.1 EXPERIMENT RESULTS: PROCESSED DATA

T_{db}	T_{wb}	T_{re}	$\bar{T}_s$	T_{mb}	M	K
34,2	32,2	39,5	37,0	39,2	263	117
17,1	11,3	36,9	26,9	35,9	243	23
14,7	10,0	37,1	26,0	36,0	247	21
35,6	33,6	39,2	37,2	39,0	191	123
36,7	34,8	39,2	38,0	39,1	142	106
23,7	17,1	36,7	31,3	36,1	128	21
21,2	15,4	36,9	29,0	36,1	122	14
37,0	35,0	38,6	37,6	38,5	104	89
25,9	17,9	36,6	31,8	36,1	99	18
35,6	33,6	38,9	37,5	38,8	190	123
34,2	32,2	38,9	37,1	38,8	251	121
13,7	9,3	37,2	25,5	36,1	230	19
35,6	33,6	38,9	37,3	38,8	195	115
36,8	34,9	39,1	37,9	39,0	152	116
38,5	36,5	38,9	38,0	38,9	63	53
37,3	35,3	38,6	37,4	38,5	106	83
12,0	9,8	36,6	23,9	35,4	185	13
13,5	10,9	36,3	24,9	35,1	149	12
16,0	13,2	36,2	26,2	35,2	128	12
19,9	14,5	36,0	27,0	35,1	77	7
33,3	31,4	37,8	35,8	37,6	190	88
33,0	31,0	38,4	36,1	38,1	254	105
34,8	32,9	37,5	36,2	37,4	100	67
34,8	32,9	37,5	35,8	37,4	96	51
33,3	31,3	37,2	34,4	37,0	99	33
36,9	35,0	37,8	36,6	37,7	59	43
35,0	32,6	38,1	36,3	37,9	186	96
36,0	34,0	38,1	36,6	37,9	138	92
37,0	35,0	38,2	37,0	38,1	101	82
33,3	31,3	37,5	35,3	37,3	184	79
36,3	34,4	37,7	36,5	37,6	100	80
37,0	34,9	37,4	36,1	37,3	54	42
21,0	19,0	37,7	27,7	36,7	236	21
26,7	24,7	37,1	32,0	36,6	118	21
31,5	29,6	37,0	33,6	36,7	60	17
28,0	26,0	37,5	32,4	37,0	229	41
29,0	27,0	37,4	32,3	36,9	168	30
31,0	29,0	37,1	33,4	36,7	85	22
36,3	34,3	37,9	36,6	37,7	103	76
37,3	35,4	37,9	36,7	37,8	60	47
34,2	32,1	37,3	35,7	37,2	135	76
31,0	29,0	37,4	34,2	37,1	182	52
31,0	29,0	37,6	35,1	37,3	252	94
33,3	31,3	37,1	34,2	36,8	93	29

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