illustrated in Figure 4.3 comprises the following basic steps:

1. compiling raw data into a file;
2. editing the file, ignoring ambiguous data, and sorting data into files;
3. processing manual data:
4. converting all thermocouple readings to true temperatures based on previously-stored calibration coefficients;
5. establishing a reference time base with zero as the time of entry into the climatic chamber;
6. establishing a baseline for radiation, convection and evaporation, based on initial and final values without a subject in the chamber, and converting radiation, convection and evaporation measurements into true quantities of heat exchange, taking into account the baseline and the day's calibration coefficients;

and

7. converting all other data such as oxygen determinations into true metabolic input heat and change in weight into evaporative heat loss.

All processed experimental data are stored and then printed. There are a total of 32 options to the programme to allow for different types of experiments. The options are specified on the three job control cards handed in with the paper tape. Many of the options occur by default if they are not specified. Some of the options are:

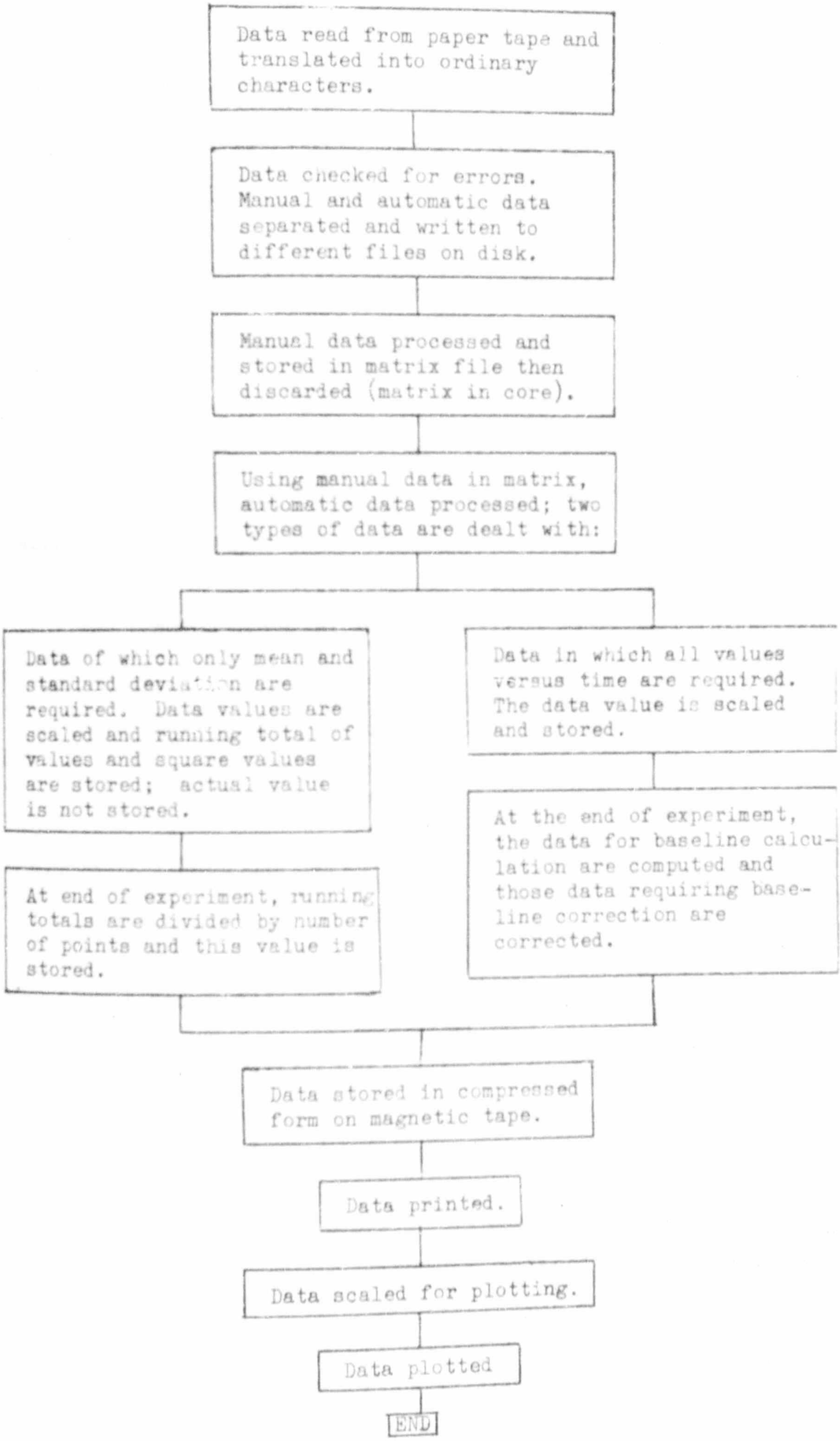


FIGURE 4.3.

A flow diagram of the computer program for processing data obtained from experiments in the climatic chamber.

1. printing and/or plotting of graphs;
2. selecting data to be plotted;
3. point-to-point or smoothed-curve plotting;
4. scaling of temperature and heat exchange axes;
5. size of graph; and
6. acceptance of new or old calibration data.

4.5 Experimental results

The information required from the results of the experiments were:

1. environmental conditions;
2. transient skin, rectal and oesophageal temperatures;
3. transient evaporative heat loss;
4. metabolic heat input;
5. work rate;
6. the final steady state temperatures; and
7. steady state heat loss by radiation, convection, the evaporation of sweat and respiratory heat loss.

Because of the number of experiments and the large amount of data it is not possible to include all the experimental results in this text. The series of experiments which contain a number of records have only one sample record illustrated in the main text and the remainder of the records are illustrated in Appendix 2.

Results of Series 1 experiments

Two resting subjects were exposed to a step change in environment from an initial comfortable environment to a variety of environments. (see Table 4.2, page 106).The transient rectal and skin temperature measurements are shown in detail in the Appendix, Figures A.14 to A.18. The recordings of metabolism and the total heat loss, that is the sum of radiative, convective and respiratory heat loss, for the last two tests in a cold environment, are illustrated in Figures A.19 and A.20. Figure 4.4, page 108, is a sample record taken from Figure A.15. The curve shows the mean transient response of subjects exposed to air moving at three different velocities when the air temperature is increased from 28°C to 40,5°C. Figure 4.5 shows the response of the subjects when exposed to a cold environment. The curves are taken from Figure A.17.

The mean steady state data from this series of experiments are listed in Table 4.7, page 111.

Results of Series 2 and 3 experiments

Two subjects initially in an environment at a temperature of 28°C, were exposed to environments at various temperatures. After a period of rest in the test environment the subjects performed work.

The third series of experiments was a repetition of the escond series but in greater detail. Because of the large quantity of data obtained only a few examples and a summary of the results are given in the text. The first half, or resting period of the experiments are the same as those of Series 1 experiment. Figure 4.6 shows a typical graph based on data obtained in the Series 3 experiments. The radiative, convective and evaporative heat exchange components including the net heat balance, or storage, are plotted. The radiation and convection components are relatively small because of the small temperature gradient between the skin and the air. The evaporative heat loss measurements determined by weighing and by direct measurement are illustrated. The results obtained by the latter method demonstrate the short-term variations in evaporation. It will be noted that the skin temperature, measured with the four-point harness is lower than that measured with the fifteen-point probe during the work period. Because of severe sweating by the subject, the harness temperature probes probably never made good thermal contact with the skin. The fifteen-point probe measurement is accepted as being the correct value of mean skin temperature. The rest period, following the period of work in the third series of experiments, is not illustrated.

Figure 4.7 illustrates the means of the experimental results obtained at three ambient temperatures and at two work rates. All the skin temperatures are based upon the fifteen-point scan measurement. It was found that humidity had little effect on skin temperature during work, unless the humidity was high, in which case the evaporative heat loss was limited (Mitchell, 1972). Figure 4.8 illustrates the means of data on evaporation obtained in the experiments of which the results are summarised in Figure 4.7. The shape of these curves are based on the mean value of the rate of increase of evaporation, the mean settling time and the mean steady state value.

Samples of the steady state experimental data for the case of one value of humidity and two values of air velocity are listed in Table 4.8.

Series 4 experimental results

The first group of Series 4 experiments were similar to Series 1 experiments in which a resting subject was exposed to a variety of warm environments. Considerable care was taken during the experiment to obtain reliable transient temperature and evaporative heat-loss records. A sample record of subject B is illustrated in Figure 4.9 . The mean skin temperature and the oesophageal temperature were measured frequently with an accurate milli-voltmeter, while the rectal temperature and the evaporative heat loss were recorded. It will be noted from the figure that the rectal and oesophageal temperatures are plotted on a larger scale than the skin temperatures are. The evaporative heat- loss record for this particular experiment is illustrated in Figure 4.10.

Further experimental records are shown in Appendix 2, Figures A21 to A25. Table 4.9 lists the steady state data.

The second group of experiments in this series required various initial values of ambient temperature and small step changes in ambient temperature. Because of the small change in temperature and because the vaso-motor tone does not change in ambient temperatures above 34°C (Chapter 5) these records are not as impressive as the previous records illustrated above. Figures 4.11 and 4.12 are typical records. Table 4.9 lists the steady state data.

Series 5 experimental results

Two subjects were cooled by transferring them from a warm environment in the preparation room to a comfortable environment in the climatic chamber. Tests were conducted at three initial room temperatures and two climatic chamber air velocities. The mean skin and rectal temperatures are summarised in the graphs in Figure 4.13. The upper curves represent data obtained when the subject was cooled in air with a velocity of 0,67 m/s and the lower curves the data obtained when the subject was cooled in air at a velocity of 3.11 m/s. The subjects had not attained a steady state temperature after a period of two hours in the climatic chamber. In order to determine their true steady state body temperatures in the climatic chamber environment, the men were placed in the climatic chamber for a long period without any initial heating in the preparation room. The mean steady state temperatures are shown in Figure 4.13. The detailed experimental records are given in Appendix 2, Figure A, 26.

No evaporation of sweat was detected in either of the experiments in the climatic chamber.

Series 6 experimental results.

A short experiment was designed to measure the rate of decrease of evaporation of sweat from a subject after he had been subjected to a sudden change from a warm to cold environment, such as in Series 5 experiments. A micro-hygrometer record is given in Figure 4.14. The recorder scale was not calibrated so that it merely shows the relative change in evaporation with time.

4.6 The temperature response of a resting man in a warm environment

Since the Series 1 experiment, the first phase of Series 2 and 3, and part of Series 4 experiments exposed different subjects to the same environment, it is worth combining all the data and all the transient records to obtain one mean transient temperature curve for each environment.

The steady state data of each subject and the calculated mean values, for four values of environment, are given in Table 4.10. Figure 4.15 shows the steady state values of rectal and skin temperature for all the experiments with an air velocity of 0,67 m/s and the air temperature ranging from 28°C to 49°C.

Figure 4.16 shows four curves which represent the transient response of man when the air temperature is increased from 28°C to 32,5°C, 35°C, 40,5°C and 49°C. These curves represent the best fit to all the transient data taken from Series 1,2,3 and 4 experiments. The initial temperatures of T_r and T_s are taken from the mean values calculated in Table 4.10.

TABLE 4.2

Experimental conditions for Series 1 experiments

Initial air temperature of preparation room = 28 °C and still air

Dry-bulb temperature (°C)	Mean radiant temperature (°C)	Wind speed (m/s)				
		0,67	1,27	1,86	3,11	4,94
		Experiment number				
12,8	12,8	1	2	3	4	5
23,9	23,9	6	7	8	9	10
35,4	35,1	11	12	13	14	15
40,4	40,6	16	17	18	19	20
49,1	49,0	21	22	23	24	25

Water vapour pressure = 10,5 ± 3,1 mbar

Experiment time schedule

Place	Rest in preparation room	Rest in climatic chamber
Time (minutes)	-60 to 0	0 to 120

TABLE 4.3

Experimental conditions for Series 2 experiments

Initial air temperature of preparation room = 28 °C and still air

Dry-bulb temperature (°C)	Mean radiant temperature (°C)	Wind speed (m/s)	Work rate (watts)		
			45	79	113
			Experiment number		
12,9	12,9	0,67	1	2	3
		3,11	4	5	6
24,1	24,1	0,67	7	8	9
		3,11	10	11	12
34,9	35,0	0,67	13	14	15
		3,11	16	17	18
43,3	43,4	0,67	19	20	21
		3,11	22	23	24

Water vapour pressure = 11,6 ± 3,6 mbar

Experiment time schedule

Place	Rest in preparation room	Rest in climatic chamber	Work in climatic chamber
Time (minutes)	-60 to 0	0 to 40	40 to 160

TABLE 4.4

Experimental conditions for Series 3 experiments

Initial air temperature of preparation room = 28 °C and still air

Vapour pressure (mbar)			20		34		46	
Work rate (watts)			45	113	45	113	45	113
Dry-bulb temperature (°C)	Mean radiant temperature	Wind speed	Experiment number					
23,9	23,8	0,67	1	2	-	-	-	-
		3,11	3	4	-	-	-	-
29,9	30,0	0,67	5	6	9	10	-	-
		3,11	7	8	11	12	-	-
34,9	35,0	0,67	13	14	17	18	21	22
		3,11	15	16	19	20	23	24
40,5	40,6	0,67	25	26	29	30	33	-
		3,11	27	28	21	32	34	-

Experiment time schedule

Place	Rest in preparation room	Rest in climatic chamber	Work in climatic chamber	Rest in climatic chamber
Time (minutes)	- 90 to 0	0 to 90	90 to 180	180 to 270

TABLE 4.5

Experimental conditions for Series 4 experiments

(Climatic chamber air velocity = 0,67 m/s)

Test No.	Subject	Rest room temperature °C	Climatic chamber dry-bulb °C	Climatic chamber wet-bulb °C
21	A	28	32,5	19
22	B			
7	A	28	35	19,4
8	B			
19	A	28	37,5	19,5
20	B			
1	A	28	40,5	21
2	B			
9	A	28	43	20
10	B			
17	A	28	46	22
18	B			
11	A	28	49	24
12	B			
3	A	32,5	40,5	21
4	B			
13	A	32,5	49	24
14	B			
5	A	35	40,5	21
6	B			
15	A	35	49	24
16	B			
17	A	37,5	40,5	21
18	B			

Experiment time schedule

Place	Rest in preparation room	Rest in climatic chamber
Time (minutes)	- 120 to 0	0 to 120

TABLE 4.6

Experimental conditions for Series 5 experiments

Initial conditions	Chamber conditions	
Dry-bulb and mean radiant temperature (°C)	Dry-bulb and mean radiant temperature (°C) = 28 °C experiment number	Air velocity (m/s)
45,0	1 2	0,67 3,11
42,0	3 4	0,67 3,11
43,0	5 6	0,67 3,11

Water vapour pressure ± 10 mbar

Experiment time schedule

Place	Rest in preparation room	Rest in climatic chamber
Time (minutes)	- 90 to 0	0 to 150

Subject characteristics

Subject	Weight kg	Height mm	Surface area m^2		Maximum oxygen intake ℓ/min.
			Total	Cycling	
D	62,2	1655	2,02	1,63	2,7
M	53,9	1655	1,88	1,53	2,5

Final steady-state data

Air Temperature °C	Air Velocity m/s	Subject	Rectal Temperature °C	Skin Temperature °C	Metabolism W	Radiation W	Convection W	Evaporation W
49	0,67	D	37,65	35,3	90	+ 140	+ 140	- 320
		M	37,65	35,9	90	+ 130	+ 155	- 330
	3,11	D	37,65	35,5	90	+ 130	+ 330	- 575
		M	38,0	36,0	85	+ 115	+ 350	- 540
40,5	0,67	D	37,4	35,55	95	+ 55	+ 40	- 190
		M	37,5	35,55	70	+ 50	+ 35	- 150
	3,11	D	37,6	35,6	75	+ 70	+ 105	- 255
		M	37,7	35,5	100	+ 70	+ 105	- 255
35	0,67	D	37,0	35,0	80	0	0	- 130
		M	37,4	35,5	-	-	-	-
	3,11	D	37,5	35,6	95	- 10	0	- 140
		M	37,8	35,2	90	- 5	+ 5	- 80
24	0,67	D	36,1	30,3	70	- 55	- 42	- 8
		M	36,3	30,5	55	- 50	- 40	- 16
	3,11	D	35,7	28,9	95	- 60	- 90	- 10
		M	36,2	29,2	125	- 55	- 90	- 10
13	0,67	D	36,1	25,1	125	- 130	- 100	0
		M	35,4	25,8	200	- 125	- 100	0
	3,11	D	35,7	22,5	200	- 100	- 250	0
		M	35,8	21,6	275	-1100	- 170	0

TABLE 4.7

SERIES 1 EXPERIMENTAL DATA

TABLE 4.8

A sample of steady-state data taken from Series 3 experiments

Subject	Weight kg	Height mm	Surface area m^2	Maximum O_2 intake litres/min.
M	56,7	1681	1,82(t) 1,58(cycling)	2.5
E	67.2	1694	1,95 - 1,64 -	3,1

Work rate	Air temp.	Wind vel.	Subject	Initial (90 m)				Rest in chamber (90 m)							Work in chamber (90m)							Rest in chamber (90 m)							Work rate
w	°C	m/s		T_r °C	T_o °C	T_s °C	M w	T_r °C	T_o °C	T_s °C	M w	R w	C w	E w	T_r °C	T_o °C	T_s °C	M w	R w	C w	E w	T_r °C	T_o °C	T_s °C	M w	R w	C w	E w	w
-45	Dry bulb = 40,5 Wet bulb = 30 ± 1	0,67	M	37.2	37.2	31.7	98	37.5	37.5	35.3	99	50	35	-260	38.1	-	36.3	300	40	75	-390	37.9	-	35.9	90	35	65	-125	-45
			E	36.5	-	30.9	95	37.1	-	35.5	95	35	75	-200	38.0	-	35.5	295	28	85	-330	38.0		36.2	108	30	70	-220	
-113			M	36.8	36.6	30.9	95	37.5	37.2	35.5	85	35	50	-185	38.2	-	35.9	545	50	110	-435	37.5	37.0	35.3	94	40	60	-230	-113
			E	36.8	36.6	30.9	88	37.2	37.1	35.7	90	44	75	-125	37.9	37.6	35.4	570	50	105	-430	37.5	37.0	36.0	95	45	75	-155	
-45		3,11	M	37.1	37.1	31.7	101	37.8	37.4	35.6	105	36	135	-270	37.8	37.4	35.4	290	40	160	-440	37.6	37.3	35.5	96	31	140	-190	-45
			E	37	36.3	29.6	104	37.5	36.9	35.5	100	34	172	-390	37.5	37.0	35.0	280	40	185	-490	37.6	37.0	35.0	98	32	160	(-320)	
-113			M	37.1	36.8	32.0	120	37.5	37.2	35.3	110	35	135	-440	38.0	37.4	35.0	550	43	180	-705	37.5	37.2	35.2	90	30	140	-255	-113
			E	37.1	37.0	30.9	115	37.3	37.2	35.3	105	36	150	-345	37.7	37.6	34.3	560	45	180	-595	37.6	37.4	35.3	99	35	160	-305	
-45	Dry bulb = 35 Wet bulb = 28	0,67	M	37.1	36.7	32.0	100	37.1	36.9	35.2	90	-5	-5	-165	37.5	37.3	34.9	275	0	-8	-180	37.6	37.3	35.2	90	-3	-8	-120	-45
			E	36.7	36.5	31.4	121	36.9	36.8	35.1	95	-8	10	-100	37.3	37.1	35.0	340	-15	10	-180	37.3	37.0	35.2	98	-26	-3	-30	
-113			M	37.3	36.9	31.9	103	37.4	37.2	35.0	115	0	5	-90	37.8	37.3	34.2	605	12	19	-460	37.5	37.0	35.0	84	0	-3	-100	-113
			E	36.8	36.6	30.3	110	37.0	36.9	35.2	85	0	-3	-30	37.6	37.4	34.2	555	5	20	-400	37.4	37.0	35.0	104	0	0	-135	
-45		3,11	M	37.0	-	31.2	97	37.2	-	35.4	89	-6	-15	-25	37.6	-	34.4	270	7	15	-220	37.4	-	35.2	87	0	0	-35	-45
			E	36.3	-	30.3	125	36.9	36.7	35.4	85	-5	0	-85	37.0	36.9	34.9	295	-5	0	-210	37.1	37.0	35.1	100	-15	-4	-55	
-113			M	36.9	36.6	31.6	109	37.1	37.0	35.5	95	-10	0	-40	38.0	37.5	34.8	605	4	35	-230	37.5	37.2	35.1	88	12	0	0	-113
			E	36.5	36.3	30.3	106	36.8	36.7	35.1	95	-5	-10	-40	37.4	36.9	34.0	600	15	38	(-410)	37.0	36.7	34.5	107	20	12	-155	
-45	Dry bulb = 30 Wet bulb = 20,8	0,67	M	36.5	36.6	30.5	86	36.6	37.0	32.7	82	-18	-27	-65	37.5	37.7	33.9	294	-26	-50	-250	37.2	37.4	34.1	90	-32	-52	-25	-45
			E	37.0	36.5	30.2	100	36.5	36.1	33.2	88	-25	-25	-45	37.0	36.7	34.1	295	-28	-45	-50	36.9	36.4	34.2	95	-33	-50	-15	
-113			M	36.7	37.0	31.8	109	37.0	37.4	33.1	86	-16	-30	-120	38.0	38.0	32.9	565	-15	-20	-650	37.1	37.3	33.9	115	-28	-40	-50	-113
			E	36.9	36.8	29.7	120	36.2	36.4	33.5	104	-25	-35	0	37.2	37.0	33.3	580	-19	-35	-370	36.8	36.8	34.4	115	-32	-45	-10	
-45		3,11	M	37.3	37.1	32.0	100	37.1	36.9	32.3	84	-15	-45	0	37.5	37.2	33.5	325	-22	-60	-150	37.3	37.3	32.7	90	-17	-55	0	-45
			E	37.1	36.9	30.0	114	36.7	36.5	32.7	105	-19	-65	-25	37.2	37.1	33.5	360	-24	-100	-150	36.7	36.6	33.0	103	-20	-90	-50	
-113			M	37.3	37.0	31.1	109	37.1	36.9	32.5	100	-17	-85	-35	38.1	37.6	34.1	560	-24	-93	-350	37.1	37.2	32.9	78	-16	-72	-46	-113
			E	37.1	36.9	30.7	110	36.5	36.4	32.5	92	-17	-30	-70	37.4	37.1	33.9	600	-12	-63	-425	36.8	36.5	32.9	90	-20	-30	-5	

T_a	Subject	T_s	T_r	T_o	H_m	H_h	H_r	H_c	H_e	H_{in}	H_{out}
28	A	33,15	36,7	36,35	92						
	B	32,25	36,6	36,5	80						
	Mean	32,7	36,65	36,42	86						
32,5	A	34,35	37,05		102	11	-20	-18	- 47		
	B	34,25	36,9		95	10	-16	-14	- 56		
	Mean	34,3	37,0		99	11	-16	-14	- 52	99	97
35	A	34,65	37,15	36,8	83	11	5	0	- 77		
	B	35,15	37,1	36,75	92	10	0	0	- 99		
	Mean		37,1	36,78	88	11	2	0	- 88	90	99
37,5	A	34,9	37,14	35,75	97	13	25	30	- 158		
	B	35,25	37,26	36,7	89	11	17	19	- 133		
	Mean	35,13	37,2	36,73	93	12	21	25	- 148	139	160
40,5	A	35,05	37,25	36,8	89	12	59	61	- 183		
	B	35,3	37,35	36,7	105	11	40	38	- 201		
	Mean	35,2	37,3	36,75	97	12	50	50	- 192	197	- 204
43	A	35,2	37,4	36,7	99	13	75	90	- 226		
	B	35,55	37,3	36,7	88	10	65	90	- 205		
	Mean	35,4	37,35	36,7	94	12	70	90	- 216	254	- 228
46	A	35,1	37,46	36,6	94,5	12	90	120	- 317		
	B	35,65	37,48	36,7	89	11	98	135	- 315		
	Mean	35,4	37,47	36,65	92	12	94	128	- 341	314	- 353
49	A	35,7	37,5	36,9	90	10	100	150	- 348		
	B	35,7	37,5	36,7	88	12	90	150	- 348		
	Mean	35,7	37,5	36,8	89	11	95	150	- 348	334	- 359

TABLE 4.9

Steady-state experimental results taken from the Series 4 experiments in the climatic chamber

TABLE 4.10

A summary of all the experimental steady-state results for the four temperatures 28 °C, 35 °C, 40,5 °C and 49 °C

T_a	Subject	T_s	T_r	T_o	H_m	H_h	H_r	H_c	H_e	H_{in}	H_{out}
°C		°C	°C	°C	W	W	W	W	W		
28	A	33,15	36,7	36,35	92						
	B	32,25	36,6	36,5	80						
	D	32,3	36,7		92						
	M	32,2	36,8		88						
	E	32,3	36,5		95						
	M	30,9	37,2	37,2	98						
	E	31,7	36,8	36,6	88						
	M	30,9	36,8	36,6	95						
MEAN		31,8	36,75	36,65	91						
sd		0,83	0,21	0,32	5,6						
35	A	34,65	37,1	36,75	92	11	5	0	99		
	B	35,15	37,15	36,8	83	10	0	0	77		
	D	35,0	37,0		80		0	0	130		
	M	35,5	37,4								
	E	35,1	36,9	36,8	95		8	10	100		
	M	35,2	37,1	36,9	90		5	5	165		
	E	35,2	37,0	36,9	85		0	3	30		
	M	35,0	37,4	37,2	115		0	5	90		
MEAN		35,1	37,13	36,89	91,4	10	2,6	3,3	98,7	97	109
sd		0,24	0,18	0,16	11,65		34	3,7	42,1		
40,5	A	35,05	37,35	36,8	105	12	59	61	183		
	B	35,3	37,25	36,7	89	12	40	38	201		
	D	35,55	37,4		95		55	40	190		
	M	35,55	37,45		70		50	35	150		
	E	35,5	37,1		95		35	75	200		
	M	35,3	37,5	37,5	99		50	35	240		
	E	35,7	37,2	37,1	90		44	75	125		
	M	35,5	37,5	37,2	85		35	50	185		
MEAN		35,43	37,34	37,06	91	12	46	52	184	189	196
sd		0,2	0,15	0,32	10		9	17,9	34,5		
49	A	35,7	37,5	36,9	90	10	100	150	348		
	B	35,7	37,5	36,7	88	12	90	150	348		
	D	35,3	37,65		90		140	140	320		
	M	35,9	37,65		90		130	155	330		
MEAN		35,65	37,6	36,8	90	11	115	149	337	354	348
sd		0,25	0,09		1,0		24	6,3	13,9		

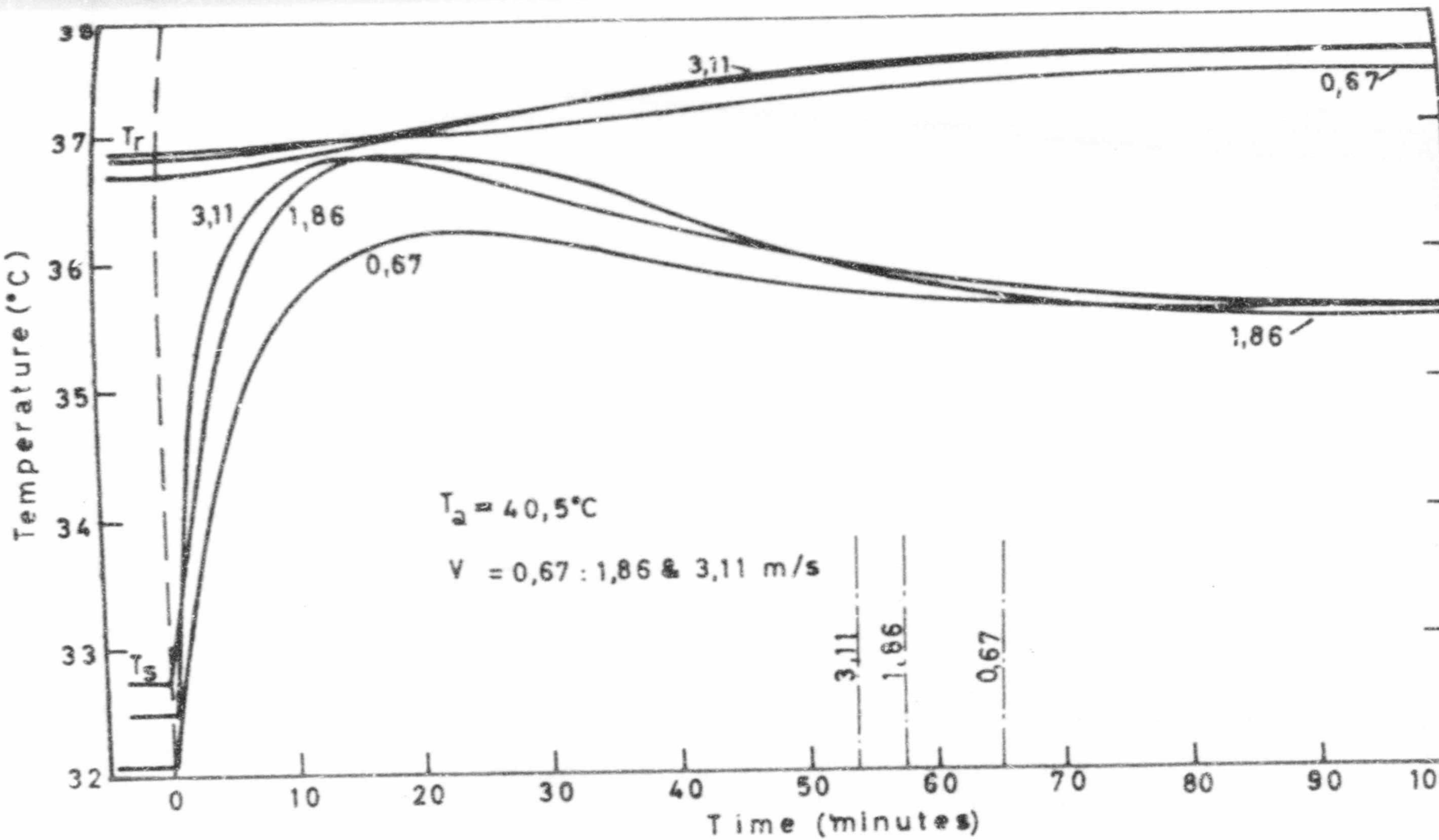


FIGURE 4.4

Series 1. Transient skin and rectal temperature for a change in air temperature from 28°C to 40,5°C.

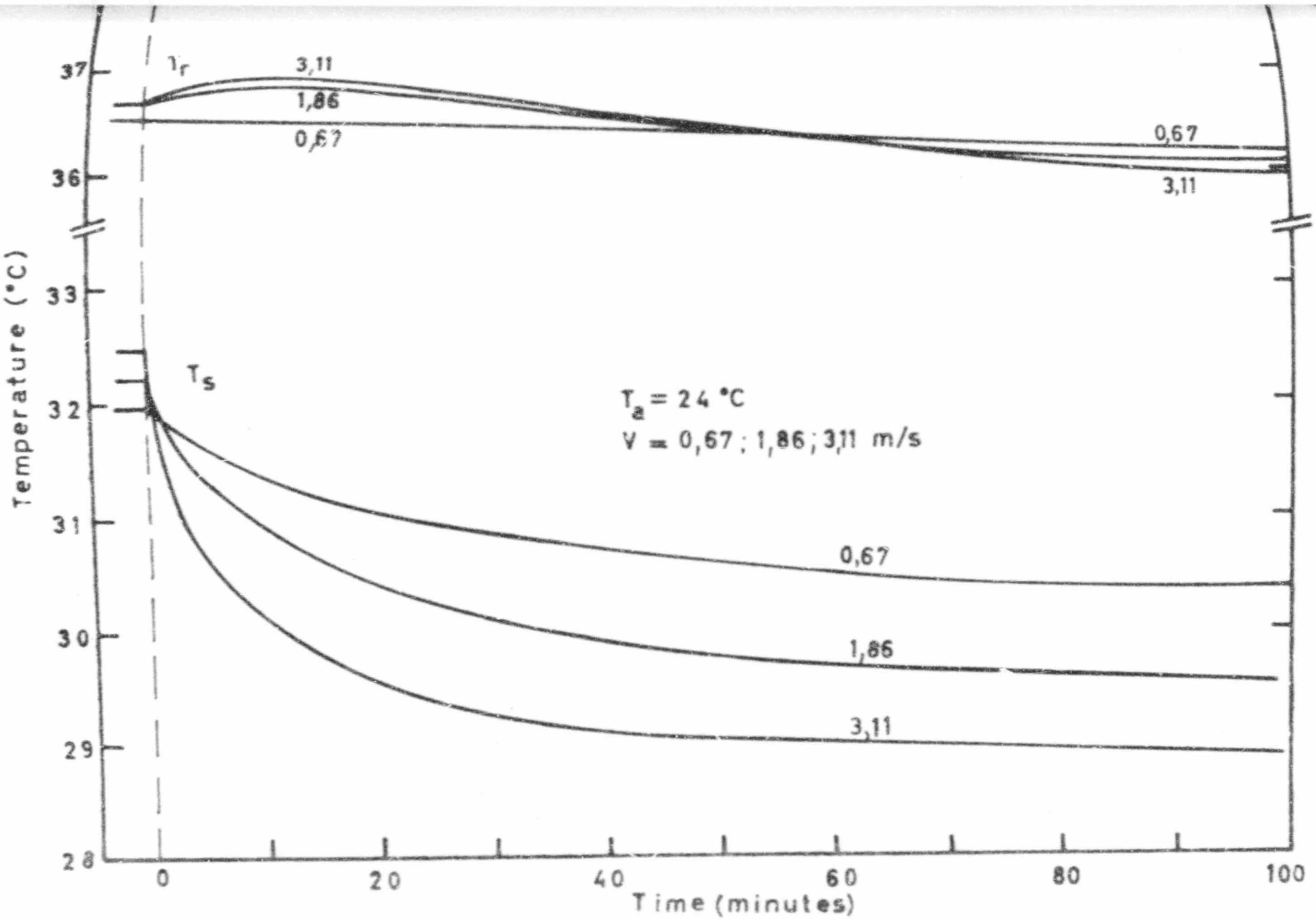


FIGURE 4.5

Series 1. Transient skin and rectal temperatures for a change in air temperature from 28°C to 24°C.

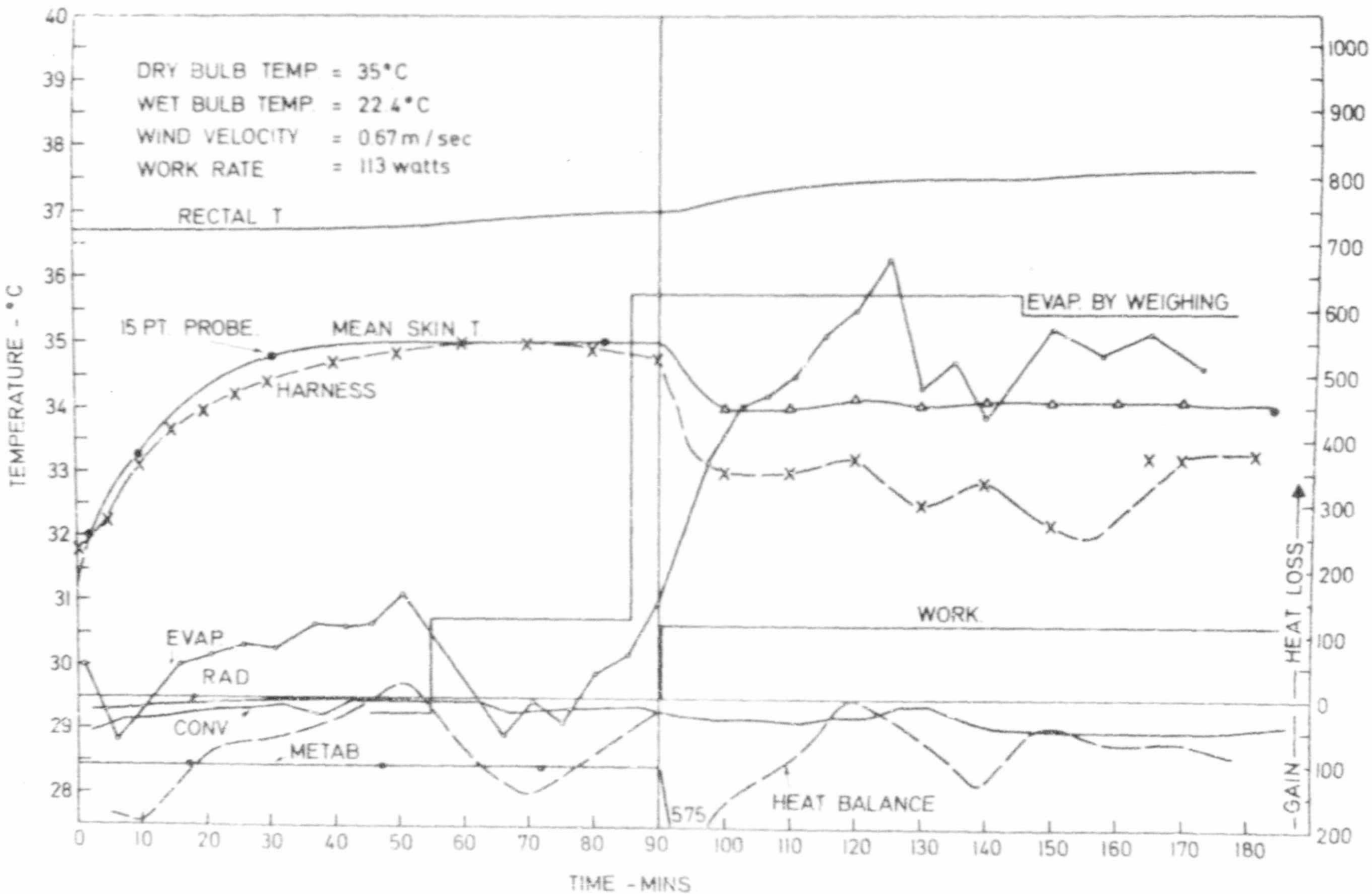


FIGURE 4.6

A Typical graph of experimental results for series 3 experiments.

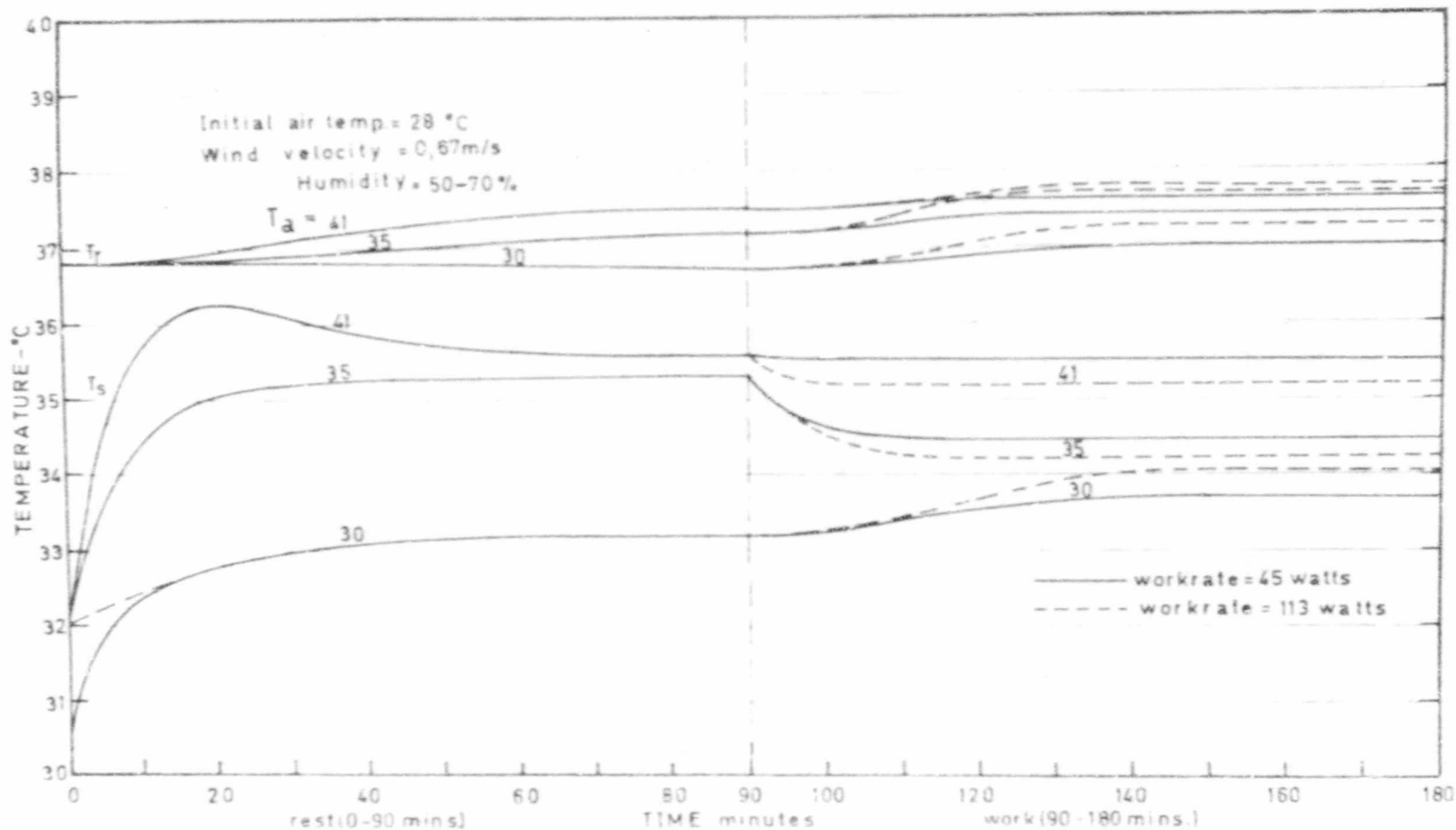


FIGURE 4.7

A summary of rectal and skin temperatures from Series 2 and 3 experiment.

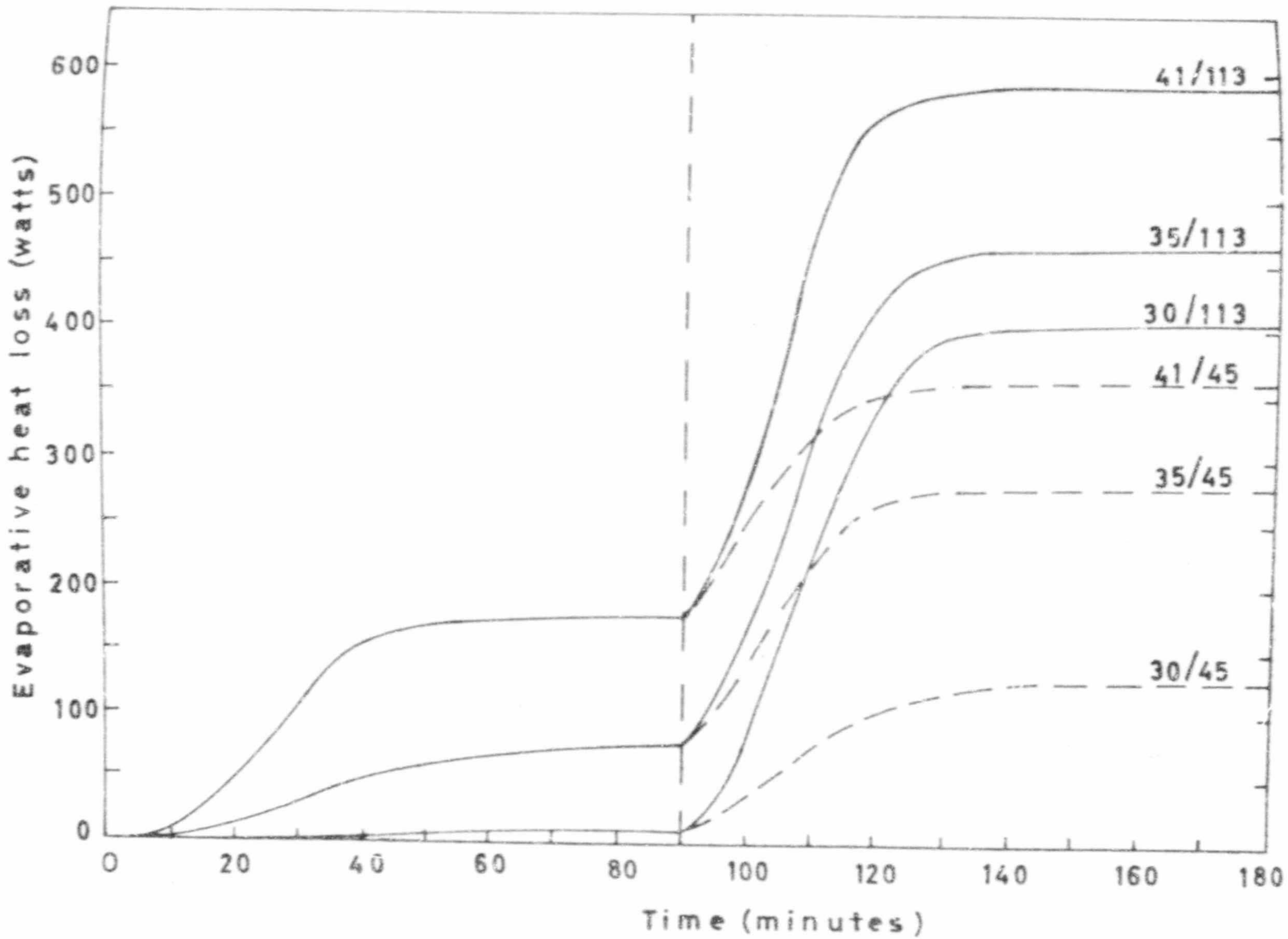


FIGURE 4.8

A summary of the mean evaporation measurements from Series 5.

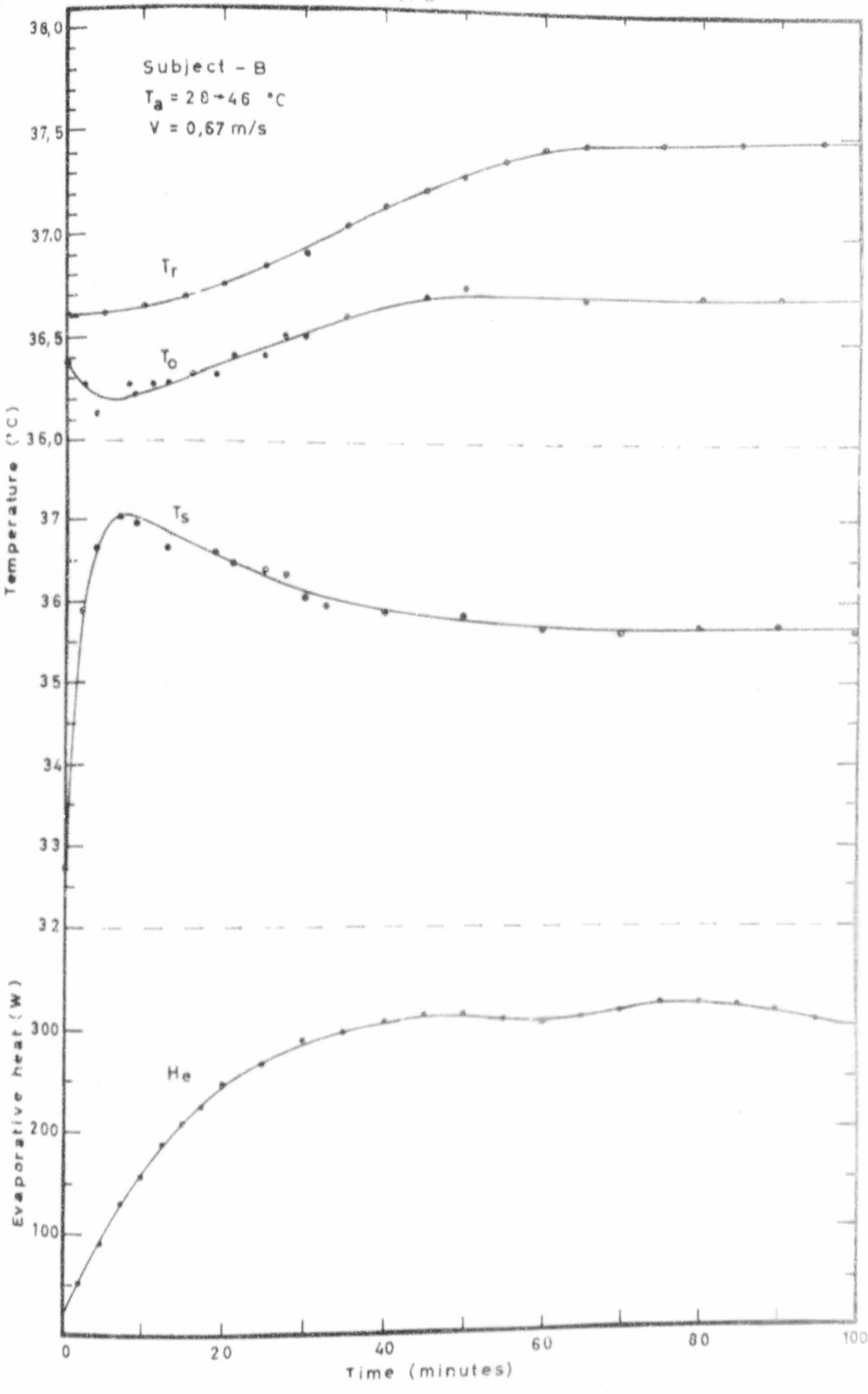


FIGURE 4.9

Experimental results for a change in temperature from 28°C to 46°C.

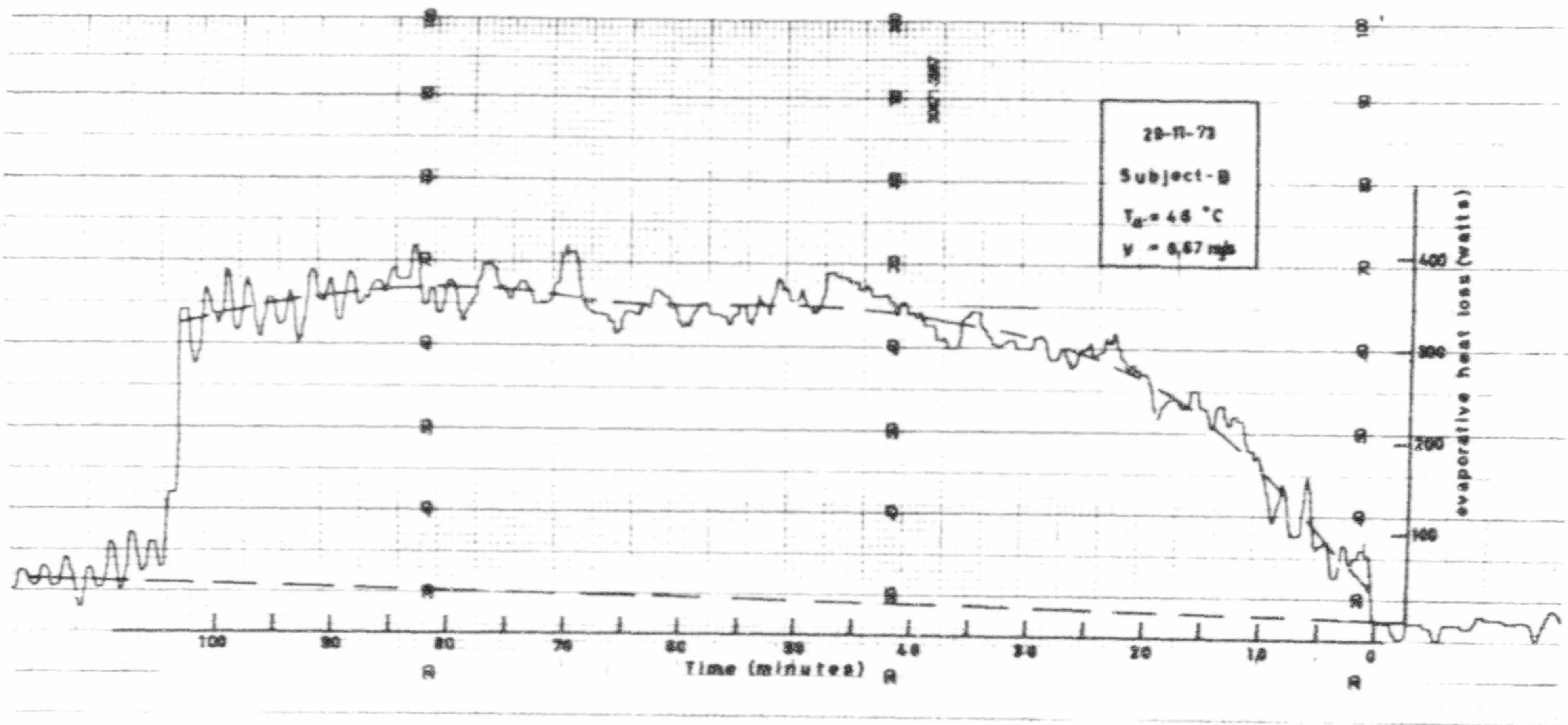


FIGURE 4.10

A typical recording of evaporative heat loss obtained in the Series 4 experiments. A resting subject was exposed to a step change in air temperature from 28°C to 46°C at time t=0. The broken lines represent the mean.

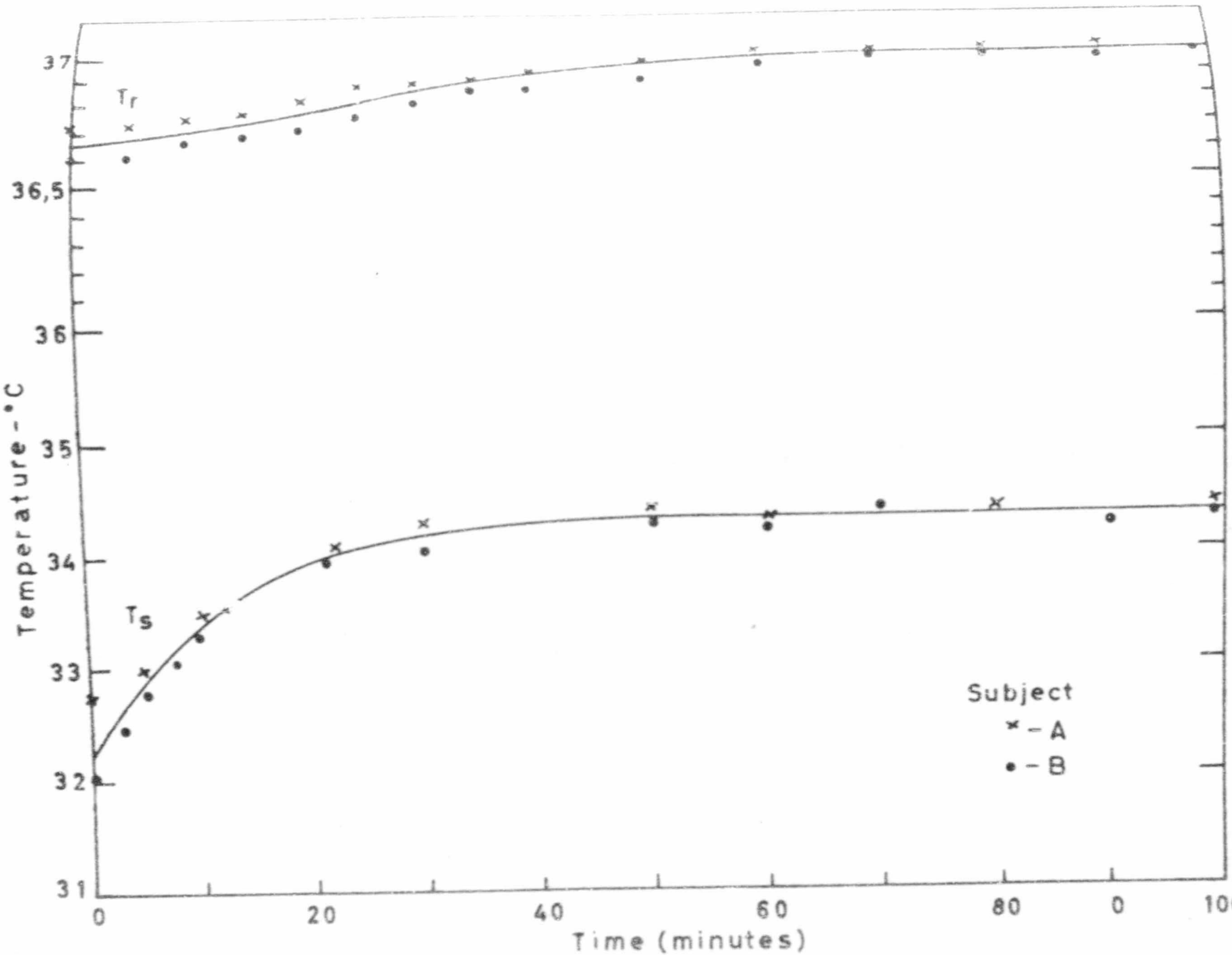


FIGURE 4.11

Experimental records of T_r and T_s for a change in air temperature from 28 °C to 32,5 °C, V= 0,67 m/s.

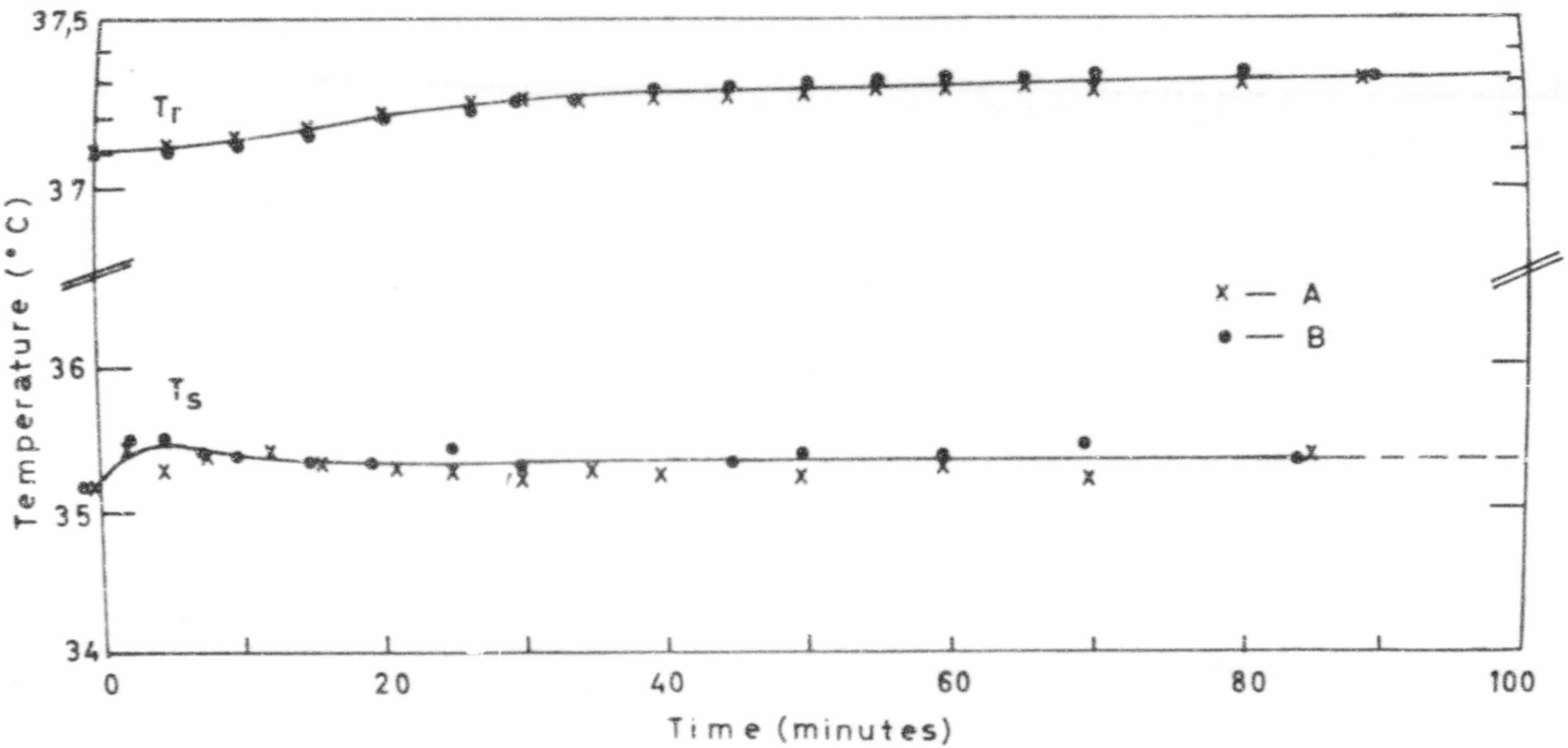


FIGURE 4.12

Experimental records of T_r and T_s for a change in air temperature from 35°C to 40,5°C.

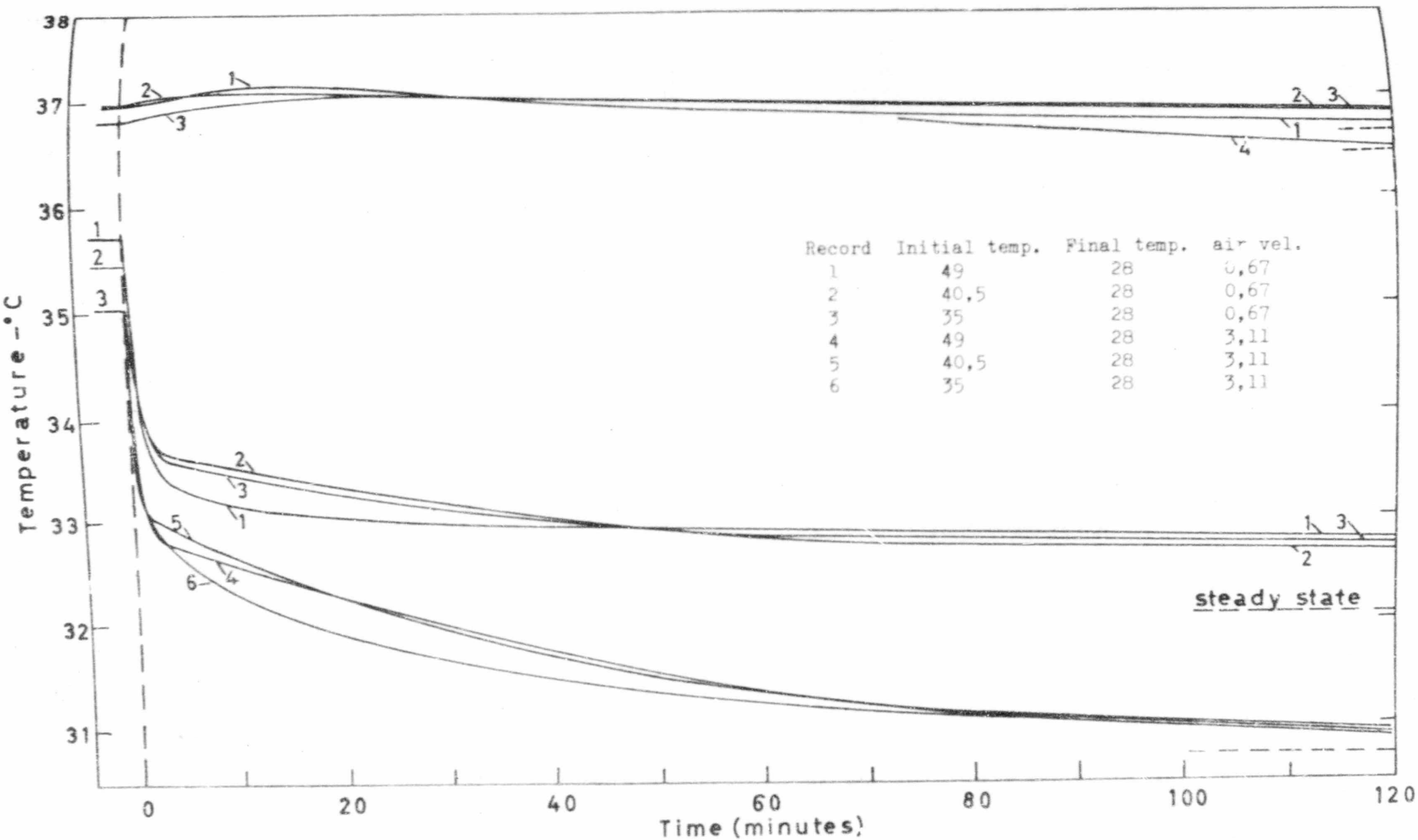


FIGURE 4.13

Transient records of T_r and T_s as the body cools from a hot environment to a neutral environment.

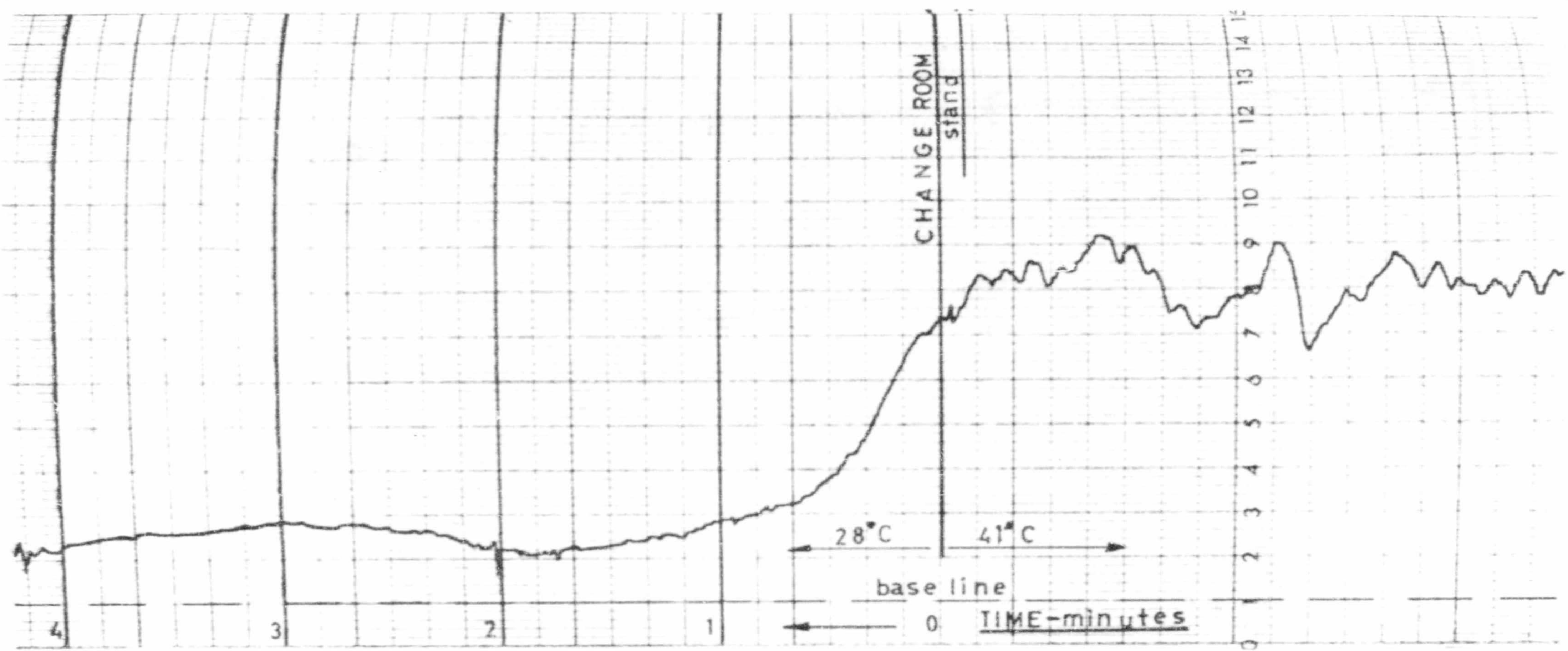


FIGURE 4.14

A recording of evaporation from a portion of the arm of a subject when cooled by transferring him from one room at 41°C to another at 28°C.

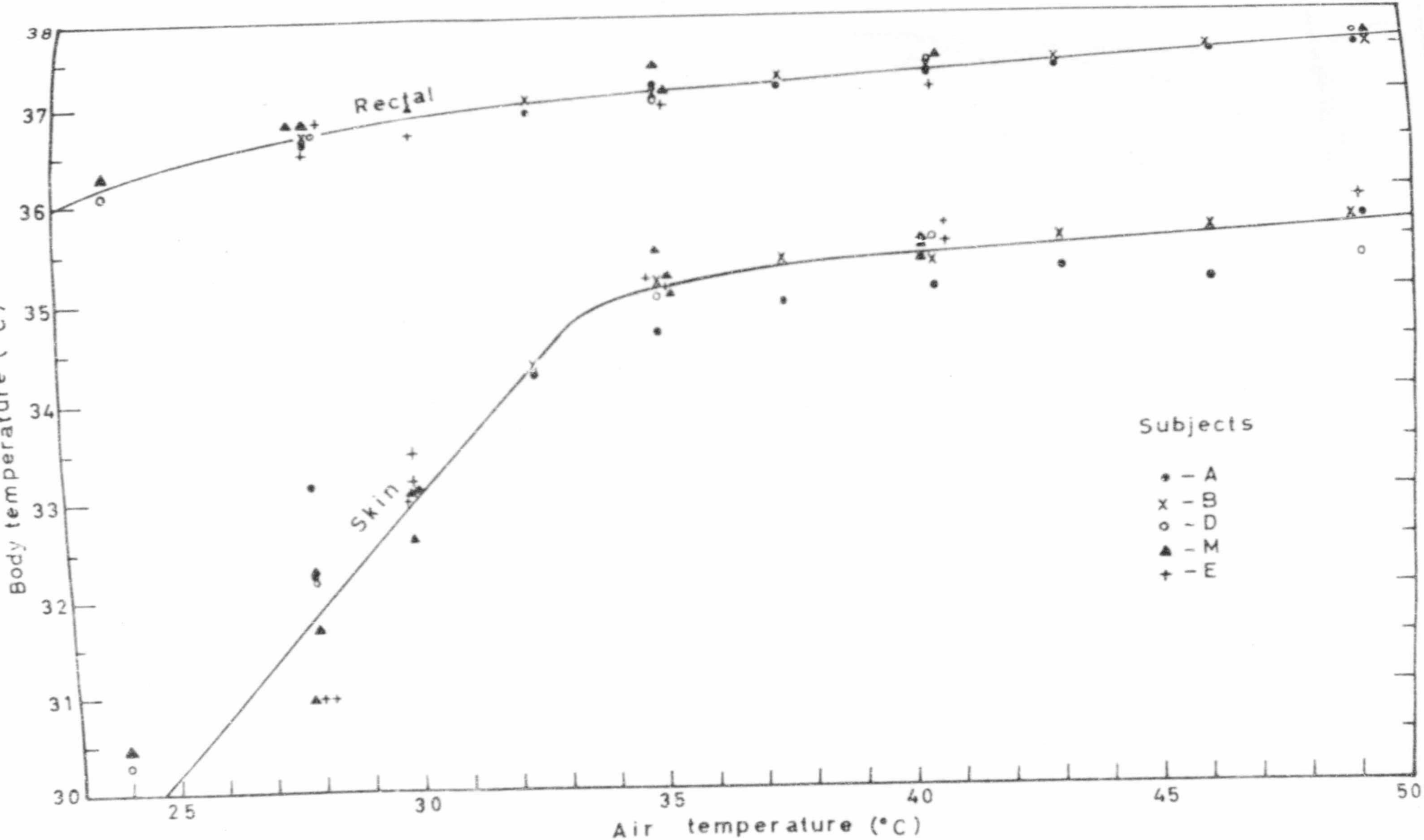


FIGURE 4.15

The steady state experimental results showing the relation between rectal temperature and air temperature and skin temperature and air temperature.

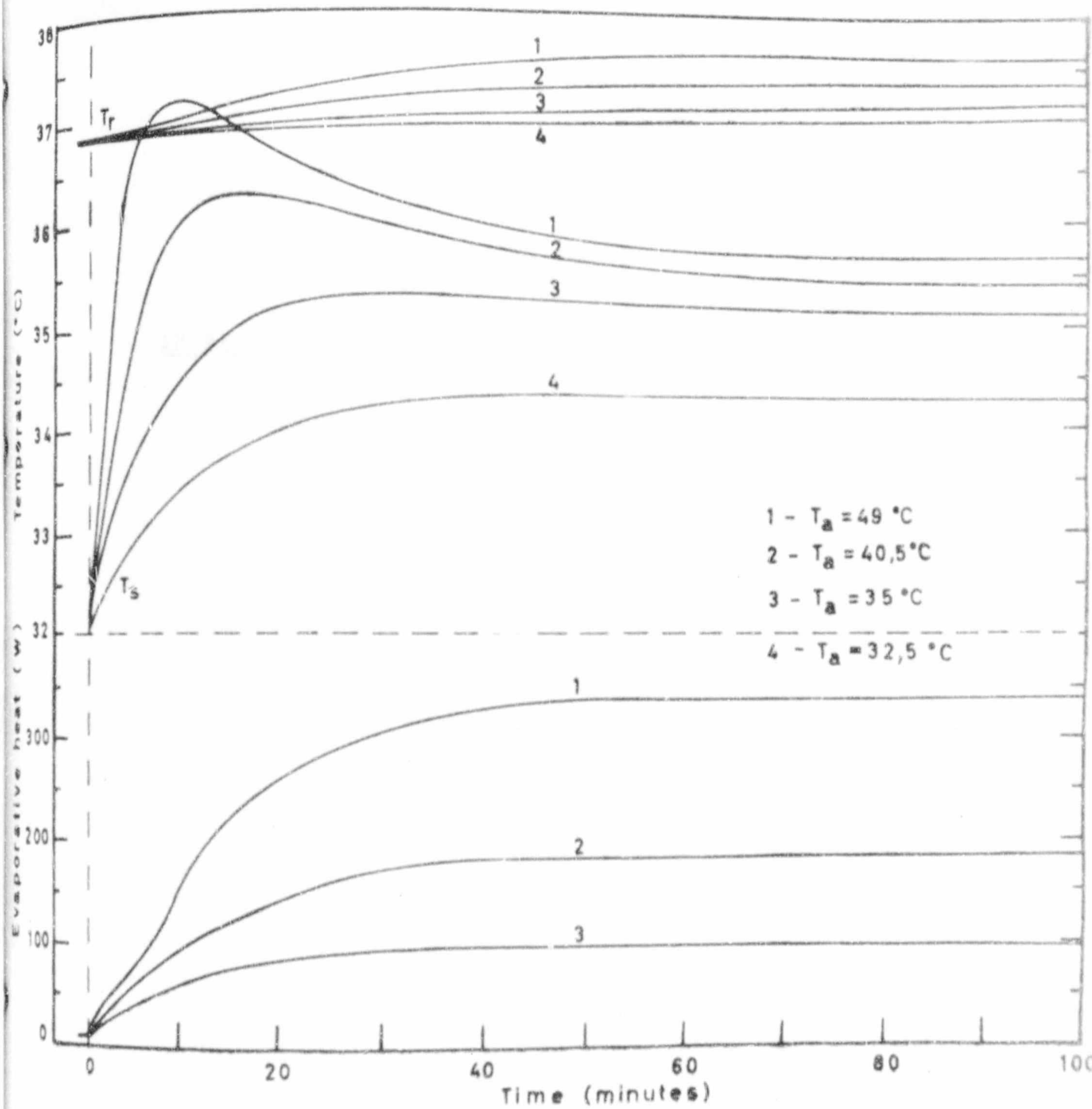


FIGURE 4.15

Experimental mean skin and rectal temperatures, and evaporative heat loss transients for a step change in air temperature from 28°C to 49°C, 40,5°C, 35°C and 32,5°C. The air velocity is 0,67 m/s.

CHAPTER 5

AN EXAMINATION OF THE THERMAL RESPONSE OF A RESTING MAN EXPOSED TO A HEAT STRESS

5.1 Nomenclature

a_1 - a_6	constants
A_b	peripheral blood flow control gain initiated by T_c
A_{bs}	peripheral blood flow control gain initiated by T_s
A_{bd}	peripheral blood flow control initiated by dT_s/dt
A_e	evaporative heat loss control gain initiated by T_c
A_{es}	evaporative heat loss control gain initiated by T_s
A_{ed}	evaporative heat loss control initiated by dT_s/dt
A_m	metabolic control gain initiated by T_c
A_{ms}	metabolic control gain initiated by T_s
C_c	core thermal capacitance (J/°C)
C_s	skin thermal capacitance (J/°C)
G_1 and G_2	steady state transfer coefficients
H_b	rate of heat flow between core and skin (W)
H_{bb}	incremental change in H_b (W)
H_e	rate of heat loss by the evaporation of sweat (W)
H_h	rate of heat loss by respiration (W)
H_{rc}	rate of heat loss by radiation and convection (W)
H_m	total metabolic heat production (W)
H_{mm}	incremental change in metabolic heat (W)
K_b	internal physiological conductance (W/°C)
K_{rc}	heat transfer coefficient for radiation and convection (W/°C)
p_1 and p_2	poles (or roots) of the transfer function
Q	substitution coefficient
R	substitution coefficient
R_b	internal resistance (°C/W)
R_{rc}	resistance representing radiation and convection heat loss (°C/W)

s Laplace operator

t time (seconds)

t_p time at which peak skin temperature occurs (seconds)

T_a air temperature (°C)

T_c core temperature (°C)

T_o oesophageal temperature (°C)

T_r rectal temperature (°C)

T_s skin temperature (°C)

$\overline{T}$ steady state incremental change in temperature (°C)

T_t and T_{ts} threshold temperatures (°C)

ΔT small transient temperature component (°C)

V air velocity (m/s)

z roots of characteristic equation

α, β and γ exponential coefficients (seconds^{-1})

τ_α and τ_β time constants (seconds)

5.2 Introduction

The thermoregulatory problem was defined and both controller and controlled system analysed in Chapter 3. The next task is to decide on the number of segments with which to represent the controlled system and then to derive the closed loop characteristic equation expressing the dependent variables in terms of the independent variables. Having established the equation, the coefficients may be determined from the experimental results.

The response of the simple model is compared with the experiments made in the climatic chamber. By examining the closed loop equation and the model's response it is possible to clarify the function of the control actions.

This chapter will examine the response of a resting man exposed to an increase in air temperature. A change in air temperature is chosen in preference to a change in air velocity or humidity as the body is more sensitive to changes in air temperature.

5.3 The closed loop transient equation of the thermoregulatory system.

As mentioned in Chapter 4, the first tests in the climatic chamber always commenced with the subject exposed to the same initial ambient temperature. The magnitude of the disturbances were increased with each test and therefore the bounds of a linear response were exceeded. It was later that the author specifically designed experiments in which the magnitude of the disturbance was small while the initial value of the ambient temperature for each test increased. The results of both types of experiments have proved valuable.

Figure 5.1 illustrates changes in the transient rectal and skin temperatures of a resting man subjected to step changes in air temperature. The curves represent the mean temperatures which were measured in the Series 1, 2, 3 and 4 experiments, described in Sec. 4.6. The oesophageal temperature is not included in the data presented in this illustration as the rectal temperature is considered to be a better indication of the dynamic core temperature on account of its large thermal inertia.

The simple smooth curves are typical of a differential equation with at least two complex roots. A second-order transient transfer expression relating either skin or rectal temperatures to the disturbances is therefore examined and the controlled system represented by two segments. A first-order expression contains only one time constant and will not discriminate between core and skin temperatures in the controlled system. Use of a higher order equation will make the analysis unnecessarily complex.

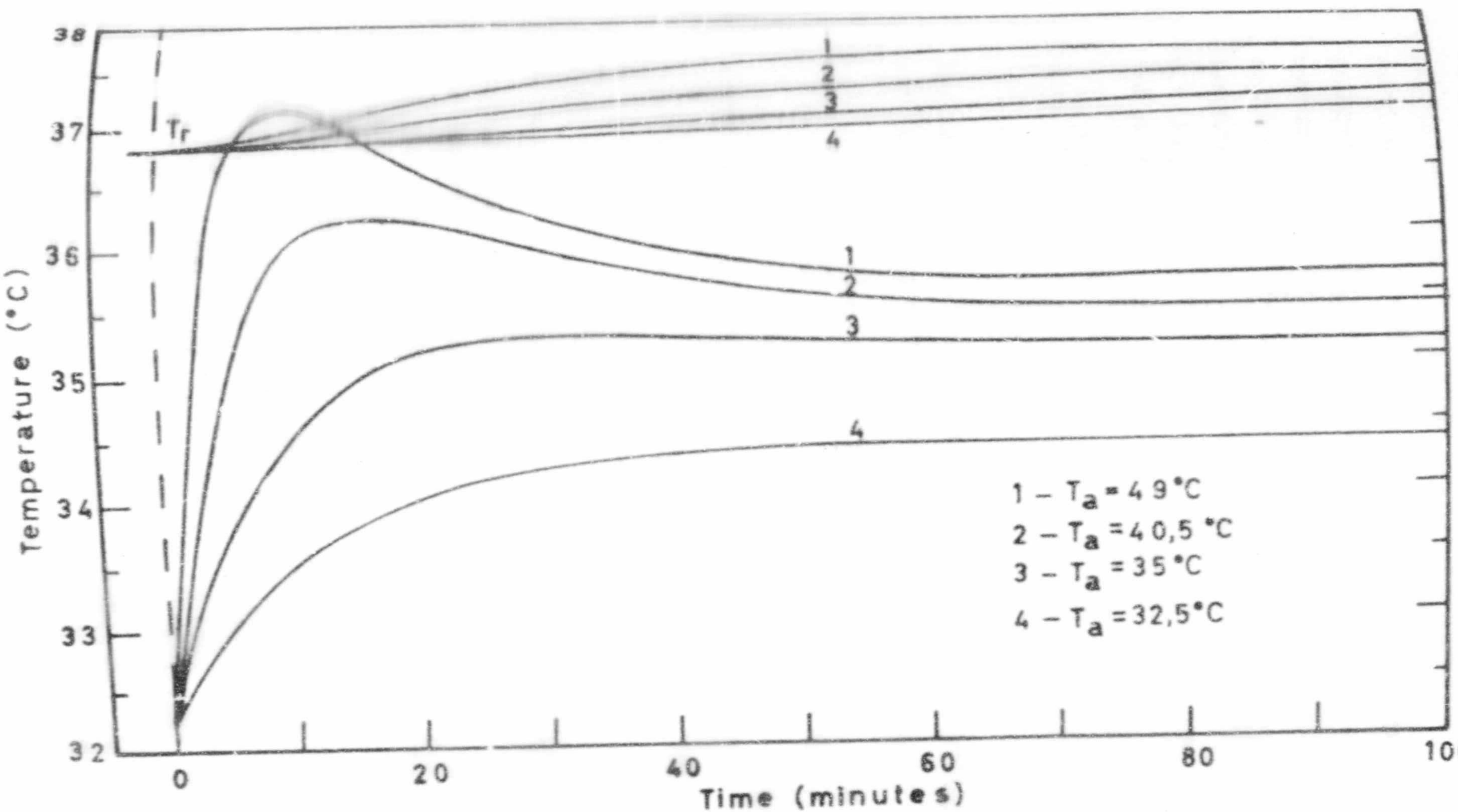


FIGURE 5.1

Mean transient rectal and skin temperatures of a man exposed to a step change in air temperature form 28°C to (1) 49°C; (2) 40,5°C; (3) 35°C and (4) 32,5°C; V = 0,67 m/s.

Consider the cylindrical model of the body illustrated in Figure 5.2. The cylinder contains two concentric sections representing the core and skin; the temperatures of these sections are T_c and T_s respectively. Metabolic heat, H_m, is generated in the core and transferred to the skin surface by conduction and vascular convection. A single apparant conductance K_b (= $1/R_b$) will represent the source of the temperature gradient between these two sections. If $H_b + \Delta H_b$ is the rate of heat transfer between the core and the skin, then

$$H_b + \Delta H_b = K_b(T_c - T_s) \quad 5\text{-}1$$

$$= 1/R_b(T_c - T_s) \quad 5\text{-}2$$

The radiative and convective heat transfer between the skin and the environment is given by equation 3- 28 as

$$H_{rc} = K_{rc}(T_s - T_a) \quad 5\text{-}3$$

$$= 1/R_{rc}(T_s - T_a) \quad 5\text{-}4$$

where $K_{rc} = (6,02 + 7,35\ V^{0,6})(\text{Surface Area})$ 5-5

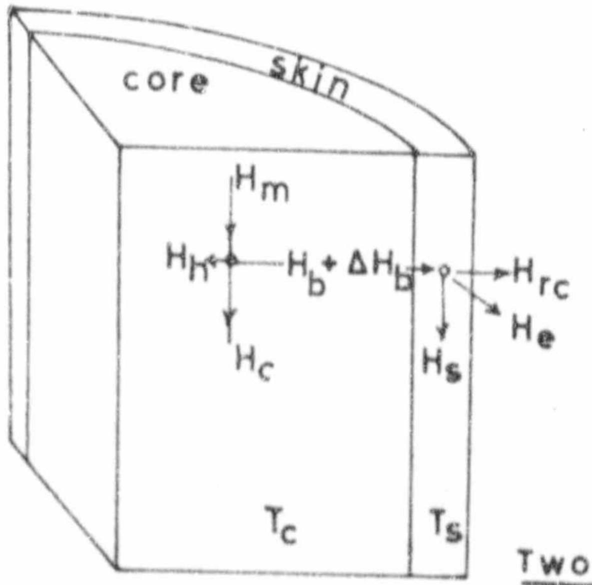
Two control actions occur in a warm environment in order to reduce the thermal stress. These actions determine the exaporative heat loss, H_e, and cause a change in the rate of heat transfer between core and skin, ΔH_b, which is due to a change in peripheral blood flow (vasomotor tone). The control actions are initiated by T_c and T_s. Assume that the control actions are proportional to T_c, T_s and the rate of change of skin temperature dT_s/dt, (refer to section 3.4).

The control characteristics may be represented by a linear equation provided that the equation is confined to a small range of temperature. Therefore

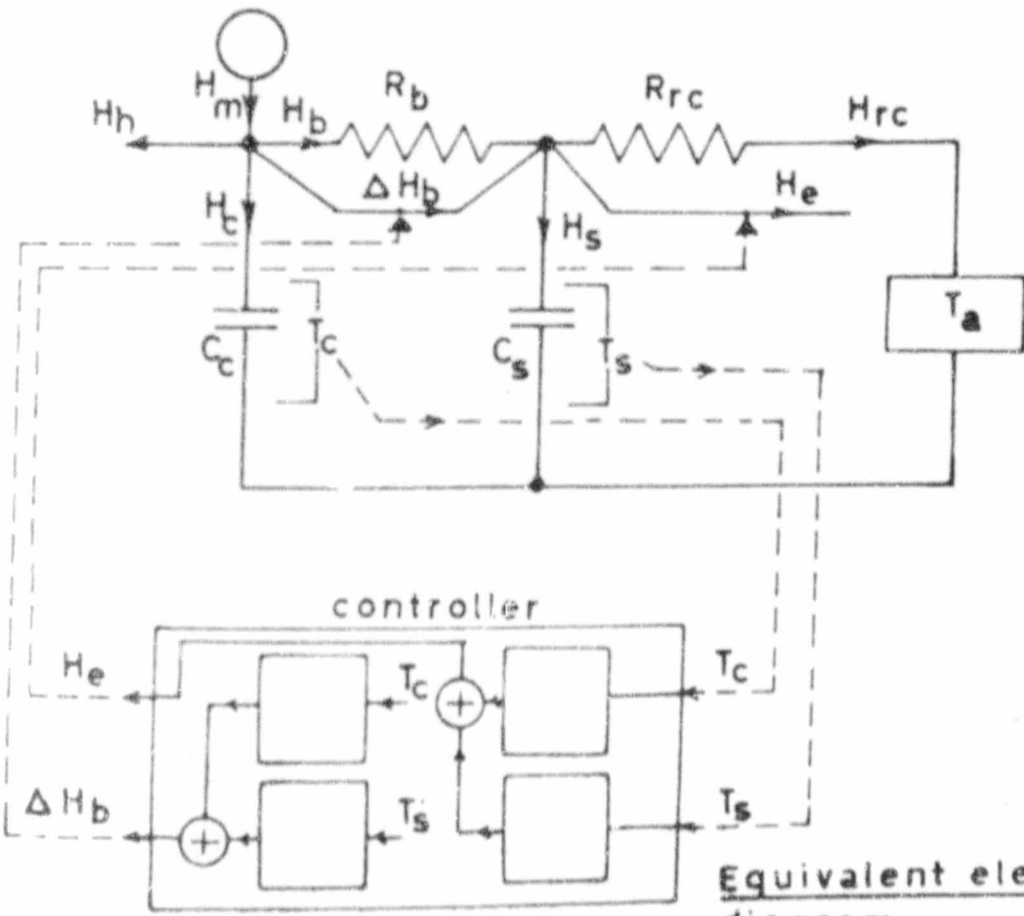
$$H_e = (T_c - T_t)A_e + (T_s - T_{ts})A_{es} + \frac{dT_s}{dt} A_{ed} \quad 5\text{-}6$$

and

$$\Delta H_b = (T_c - T_t)A_b + (T_s - T_{ts})A_{bs} + \frac{dT_s}{dt} A_{bd} \quad 5\text{-}7$$



Two segment model



Equivalent electrical diagram

FIGURE 5.2

The simple second-order model with its equivalent electrical network diagram.

where A_b is the control sensitivity between ΔH_b and T_c
A_{bs} " " " ΔH_b and T_s
A_{bd} " " " ΔH_b and dT_s/dt
A_e " " " H_e and T_c
A_{es} " " " H_e and T_s
A_{ed} " " " H_e and dT_s/dt

With the exception of the muptiplication term, which is considered later, the equations 5-6 and 5-7 are the same as the controller equation 3-12. The coefficients A_b, A_{bs}, A_e and A_{es} represent the slope of the particular section of the curve and T_t and T_{ts} the intercept of the straight line if it is extended to cut the temperature axis. The terms T_t and T_{ts} do not represent a set point.

The closed loop transient temperature expressions describing T_c and T_s in terms of a small step-change in T_a may now be derived using equations 5-1 to 5-7. The equations may be derived from first principles or simply by the use of a signal flow diagram and Mason's loop rule. The signal flow diagram and the closed loop equation are given in Figure 5.3 The analysis is in Appendix A4 . At a first glance the transient expressions are complex, but they are, in fact, second order equations with the same form as equations 3-2 and 3-3.

The equations may be expressed as

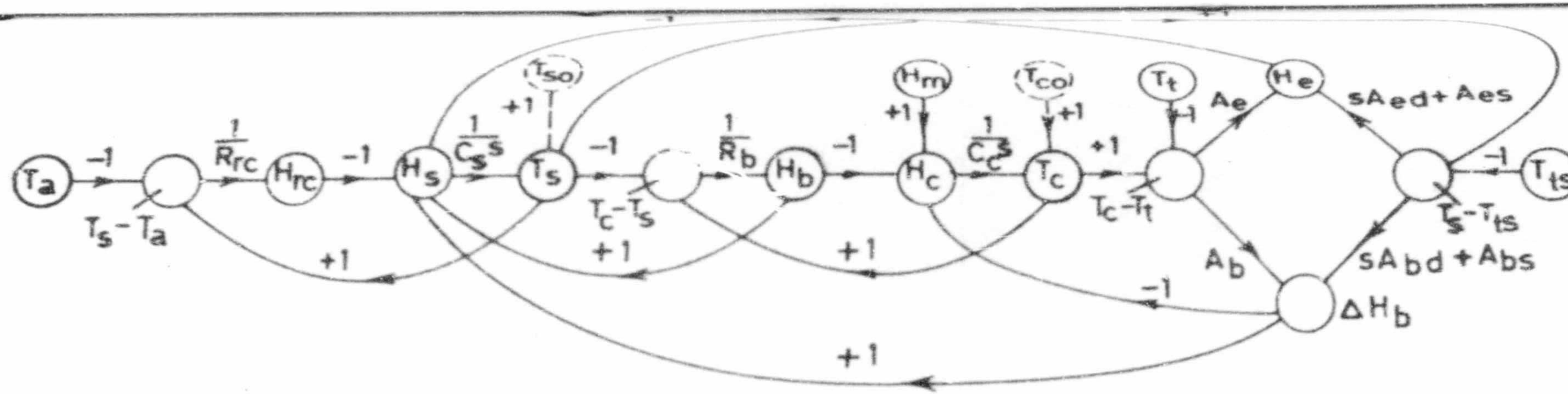
$$\Delta T_c(s) = \frac{G_1(s + \gamma_1)}{s^2 + Qs + R} \Delta T_a(s) \qquad 5\text{-}10$$

$$= \frac{G_1(s + \gamma_1)}{(s + \alpha)(s + \beta)} \Delta T_a(s) \qquad 5\text{-}11$$

and

$$\Delta T_s(s) = \frac{G_2(s + \gamma_2)}{s^2 + Qs + R} \Delta T_a(s) \qquad 5\text{-}12$$

$$= \frac{G_2(s + \gamma_2)}{(s + \alpha)(s + \beta)} \Delta T_a(s) \qquad 5\text{-}13$$



$$\frac{\dot{T}_c(s)}{\dot{T}_a(s)} = \frac{1 - R_bA_{bs} - sR_bA_{bd}}{s^2\left[R_bR_{rc}C_cC_s(1 + 1/C_s(A_{ed} - A_{bd}))\right] + s\left[C_c(R_b + R_{rc} + R_bR_{rc}(A_{es} - A_{bs})) + C_s(P_{rc} + A_bR_bR_{rc}) + A_{ed}R_{rc} + R_bR_{rc}(A_bA_{ed} - A_eA_{bd})\right] + \left[1 + A_eR_{rc} + A_bR_b + A_{es}R_{rc} + R_bR_{rc}(A_bA_{es} - A_eA_{bs})\right]} \qquad 5\text{-}8$$

and

$$\frac{\dot{T}_s(s)}{\dot{T}_a(s)} = \frac{(1 + R_bA_b) + sR_bC_c}{s^2\left[R_bR_{rc}C_cC_s(1 + 1/C_s(A_{ed} - A_{bd}))\right] + s\left[C_c(R_b + R_{rc} + R_bR_{rc}(A_{es} - A_{bs})) + C_s(R_{rc} + A_bR_bR_{rc}) - A_{ed}R_{rc} + R_bR_{rc}(A_bA_{ed} - A_eA_{bd})\right] + \left[1 + A_eR_{rc} + A_bR_b + A_{es}R_{rc} + R_bR_{rc}(A_bA_{es} - A_eA_{bs})\right]} \qquad 5\text{-}9$$

FIGURE 5.3

A signal flow diagram of the thermoregulatory system and the closed loop equations.

where $$G_1 = \frac{-A_{bd}}{R_{rc}C_cC_s(1 + (A_{ed} - A_{bd})/C_s)} \qquad 5\text{-}14$$

$$Y_1 = \frac{-(1 - R_bA_{bs})}{A_{bd}R_b} \qquad 5\text{-}15$$

$$G_2 = \frac{1}{R_{rc}C_s(1 + (A_{ed} - A_{bd})/C_s)} \qquad 5\text{-}16$$

$$Y_2 = \frac{1 + R_bA_b}{R_bC_c} \qquad 5\text{-}17$$

$$Q = \frac{(R_b + R_{rc} + R_bR_{rc}(A_{es} - A_{bs}))C_c + (R_{rc} + A_bR_bR_{rc})C_s + A_{ed}R_{rc} + R_bR_{rc}(A_bA_{ed} - A_eA_{bd})}{R_bR_{rc}C_cC_s(1 + (A_{ed} - A_{bd})/C_s)} \qquad 5\text{-}18$$

$$R = \frac{1 + R_bA_b + R_{rc}(A_e + A_{es}) + R_bR_{rc}(A_bA_{es} - A_eA_{bs})}{R_bR_{rc}C_cC_s(1 + (A_{ed} - A_{bd})/C_s)} \qquad 5\text{-}19$$

$$\alpha = \frac{Q + \sqrt{Q^2 - 4R}}{2} \qquad 5\text{-}20$$

$$\beta = \frac{Q - \sqrt{Q^2 - 4R}}{2} \qquad 5\text{-}21$$

If $\Delta T_a(s)$ is a step disturbance of magnitude ΔT_a then it is represented by

$$\Delta T_a(s) = \frac{1}{s}\,\Delta T_a \qquad 5\text{-}22$$

in the above expressions.

The numerical solutions of the closed loop equations 5-11 and 5-13, which give the 'real time' value of ΔT_c and ΔT_s are obtained from the inverse Laplace transform tables (Holbrook, 1959) and are given by

$$T_c(t) = (a_1 + a_2e^{-\alpha t} + a_3e^{-\beta t})\,\Delta T_a \qquad 5\text{-}23$$

and

$$T_s(t) = (a_4 + a_5e^{-\alpha t} + a_6e^{-\beta t})\,\Delta T_a \qquad 5\text{-}24$$

where $a_1 = G_1 \gamma_1/\alpha\beta$ 5-25

$$a_2 = G_1(\alpha - \gamma_1)/(\alpha(\beta - \alpha)) \quad 5\text{-}26$$

$$a_3 = G_1(\beta - \gamma_1)/(\beta(\alpha - \beta)) \quad 5\text{-}27$$

$$a_4 = G_2\gamma_2/\alpha\beta \quad 5\text{-}28$$

$$a_5 = G_2(\alpha - \gamma_2)/(\alpha(\beta - \alpha)) \quad 5\text{-}29$$

$$a_6 = G_2(\beta - \gamma_2)/(\beta(\alpha - \beta)) \quad 5\text{-}30$$

Both $\Delta T_c(t)$ and $\Delta T_s(t)$ consist of a steady state increment and two decaying exponential terms. The actual values of T_c and T_s are given by the transient values plus the initial value before the step change.

The coefficients requiring identification are A_b, A_{bs}, A_{bd}, A_e, A_{es}, A_{ed}, C_c, C_s, R_{rc} ($= 1/K_{rc}$) and R_b ($= 1/K_b$). Note that the terms T_t and T_{ts} do not appear in these equations so that they therefore do not determine the magnitude of the transient response under consideration.

5.4 Identifing the coefficients of the closed loop equations

The coefficients R_b, R_{rc}, C_c and C_s may be determined directly from the experimental data. The control coefficients A_b, A_{bd}, A_{bs}, A_e, A_{ed} and A_{es} are derived after an examination of the systems response.

The value of R_b ($= 1/K_b$) is dependent upon the peripheral blood flow or 'vasomotor tone'. The steady state value, for each value of T_a which was examined, may be calculated from the data in Table 4.10 using equation 5-2. That is

$$R_b = 1/K_b = \frac{T_c - T_s}{H_b} \quad 5\text{-}31$$

where $H_b = H_m - H_h$